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Cover design: The four subjects symbolize the diversity of sciences embraced by the Royal Society of Western Australia. Mangles' kangaroo paw (*Anigozanthos manglesii*) and the numbat (*Myrmecobius fasciatus*) are the floral and faunal emblems of Western Australia, and stromatolites are of particular significance in Western Australian geology (artwork: Dr Jan Taylor). The Gogo Fish (*Mcnamaraspis kaprios*) is the fossil emblem of Western Australia (artwork: Danielle West after an original by John Long).

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Coastal geoheritage: encompassing physical, chemical, and biological processes, landforms, and other geological features in the coastal zone

M Brocx[1] & V Semeniuk[2]

[1] Division of Science & Engineering
Murdoch University, South St., Murdoch, WA, 6150
[2] V & C Semeniuk Research Group
21 Glenmere Rd., Warwick, WA, 6024

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Abstract

The coast is one of the most complex environments on the Earth's surface, being a zone of intersection and interaction of land, sea, groundwater, and atmosphere and the processes therein, and carries processes and products that are either not present or only weakly developed elsewhere. With other matters such as lithology, structure, or geological framework being equal, the coastal zone is one that generally results in greater geodiversity than elsewhere. The range of interacting physical, chemical and biological processes in the coastal zone include: waves, tides, storms, and cyclonic activity (all resulting in erosion, sediment mobility, particle size sorting, sedimentary structures); development of a splash zone; onshore winds resulting in shore-directed wind waves and longshore drift, and in erosion, transport, particle sorting, lag deposits, and dune building; sedimentation mediated physically by fluvial influx, longshore and/or onshore transport, and tidal currents, or biologically by skeletal production; bioerosion; chemical erosion; salt weathering; tidal invasion of coastal sedimentary bodies by seawater; evaporation and transpiration; hydrochemical effects such as solution, or precipitation of carbonates, gypsum, or halite; fresh-water seepage and its effect on ecology and coastal erosion; sediment delivery fluvially; and biological effects including skeletal production, encrustation, biostrome and bioherm building, grain fragmentation, and bioturbation. A significant factor also is the prevailing nature of many of the processes therein. Coasts commonly exhibit shore-normal environmental gradients and hence a graded expression of processes, resulting in variation in complexity and geodiversity in physical, geochemical and biological products across the shore, and variation in fine- to small-scale stratigraphic sequences. To provide a perspective of the expression of any geodiversity of bedrock, and of the diversity and complexity of sedimentary systems in the coastal zone, selected coastal zones are compared with terrestrial environments for specific rock types, and specific sedimentary sequences – while there is overlap, coastal environments present greater complexity and geodiversity of physical, chemical and biological products. Because they interface with oceans, coastal deposits and coastal forms also can record a history of sea level, climate, and oceanic processes. It is the range of sedimentological and erosional features, expressed geomorphologically and stratigraphically along the coast, and their strength of development, that sets coastal geoheritage apart from continental (or inland) geoheritage.

Keywords: coastal geoheritage, coasts, geoheritage, geoconservation, geodiversity

Introduction

Geoheritage, a term evolved from and synonymous with "geological heritage" (Anon 1991a; Joyce 1994; O'Halloran *et al.* 1994; Brocx & Semeniuk 2007), and now used internationally, as well as in Australia, carries the notion of the heritage of features of a geological nature. The terms were recently afforded formal status, beyond their use in geoconservation and environmental management, by the launching of a new Journal, *Geoheritage*, entirely devoted to the issues of geological heritage, geoconservation, theory and ideas underpinning geoheritage and geoconservation, and management of sites of geological significance, and by the International Union of the Conservation of Nature (IUCN 2008) as Resolution 4.040 Conservation of geodiversity and geological heritage (adopted as CGR4.MOT055), adding geoheritage to its conservation agenda.

In its scope, the general term *geoheritage* encompasses intrinsically important, or culturally important geological sites that are of global, national, state-wide, to local significance (Brocx & Semeniuk 2007) that include igneous, metamorphic, and sedimentary rocks, and stratigraphic, structural, geochemical, mineralogic, palaeontologic, geomorphic, pedologic, and hydrologic features, at all scales, that offer information or insights into the formation or evolution of the Earth, or into the history of science, or that can be used for research, teaching, or reference. Sharples (1995) expanded the original idea of geoheritage to include the protection of dynamic geological processes and geodiversity for their inherent or intrinsic values. Geodiversity is the term used to denote the diversity of geological features present at a given site or region (Brocx & Semeniuk 2007).

Features of geoheritage significance are to be found in many locations and environments around the globe, and can range from crystal-scale, fossil-scale, bedding-scale, cliff-scale, to systems scale (see Figure 2 in Brocx & Semeniuk 2007). Examples include: (as crystals) the Jack Hills Archaean zircons in Western Australia (Wilde *et al.* 2001; Cavosie *et al.* 2004), (as fossils) the Precambrian Ediacaran fauna in South Australia (Glaessner 1966), (as bedding-scale features) the eurypterid tracks on rippled sandstone in the Tumblagooda Sandstone in Western Australia, (at cliff scale) the unconformity at Siccar Point in Scotland, and (at systems scale) the Grand Canyon in the USA and the Shark Bay area in Western Australia (Holmes 1966; Shelton 1966; Logan & Cebulski 1970; Logan *et al.* 1970; Playford 1990). From a location perspective, sites of geoheritage significance occur in a variety of landscape settings, climatic settings, and geological provinces, from eroding landscapes in arid zones (Monument Valley, Arizona) to eroding landscapes in alpine regions (Mount Blanc, Switzerland). Each may carry with it relatively simple processes and products or an array of complicated and interacting processes and products. Thus, there is quite a variety of recognised sites of geoheritage significance in the world, some significant because of their crystals and fossils, some because of their large-scale attributes, such as structural/tectonic features, and some because of the collective ensemble of a suite of large-scale to fine-scale features involving geological, geomorphological, lithological, and pedological attributes, amongst others (*e.g.*, Shark Bay). In this context, geoheritage addresses the importance of geological sites in their complexity, diversity, and values scientifically, culturally, educationally, and for reference and research.

Of all the environments on the Earth's surface, one of the most complex is the shore zone. With other matters such as lithology, geological structure, or geological framework being equal, it is an environment that results in more complexity and geodiversity (*i.e.*, varied assemblage of geological features) than other environments represented elsewhere. As with other environments, the complexity and geodiversity developed along the coast are variable according to parent rock types, sediments, and other materials, biodiversity, hydrochemical effects, diagenesis, and variable according to environmental setting and climate.

In this paper we explore the various features of geology (and geomorphology as a subset of geology), expressed as geodiversity in the coastal zone as a prelude to identifying coastal types and sites that may have geoheritage significance (to be developed in later works). Under the umbrella term, *coastal geoheritage*, we explore the reasons for coastal geodiversity, *i.e.*, the physical, chemical, and biological processes, landforms, and other geological features that occur in the coastal zone, and formally recognise that coastal geodiversity and coastal geoheritage are especially significant in a context of geoconservation. To place the complexity of the coastal zone in perspective, and hence the geodiversity of the coastal zone into perspective, rocks and sediments in the coastal zone are compared with those in terrestrial environments, *e.g.*, a Pleistocene calcarenite exposed at a rocky shore with that exposed in an inland cliff, and an accreting upward-fining sequence of tidal flat sediment with that of a point bar, amongst other examples.

The term bedrock is used in this paper to refer to indurated rocks of sedimentary, igneous, and metamorphic origin, of Precambrian to Phanerozoic age (*e.g.*, the Silurian Tumblagooda Sandstone, and the Mesozoic Broome Sandstone), and not only to Precambrian basement rocks.

Definition of *coast* and *coastal*, and other terms

The term "coast" and its derivatives are reviewed and then defined here because the ideas of geoheritage and geoconservation will be applied to this very specific site of the Earth's environment.

Few texts define the term *coast*. Even encyclopaedia devoted to geomorphology (Fairbridge 1968), or to beaches and coastal environments (Schwartz 1982) do not address its definition, but rather focus on using its derivative as an adjectival descriptor, *e.g.*, *coastal* classification, *coastal* ecology, *coastal* erosion, and so on. A brief review of those texts dealing with coastal systems where the definition of *coast* is somewhat addressed (although not to any depth) is presented below.

Reineck & Singh (1980) use the term *coast* as the zone that separates continents from the sea. Davis (1978) defines a *coastal area* as the zone where land and sea meet, where there can be a variety of complex environments. Bates & Jackson (1987) define *coast* as the strip of land of indefinite width that extends from the low tide line inland to the first major change in landform feature. Woodroffe (2002) defines *coast* as the interface between land and sea.

In all definitions, generally, the term *coast* is applied to shoreline environments, usually for the strip of land that is located between high and low tide. Some authors extend the use of the term to environments in the nearshore breaker zone and extending to the nearshore supratidal zone. In Western Australia, for planning purposes, the *coast* is defined to include the coastal waters to a depth of 30 m, as well as reefs, estuaries, tidal rivers and land which is presently subjected to coastal processes (such as mobile dunes, areas inundated by storm surge, and vegetated foreshore areas exposed to onshore winds). In addition, the *coast* includes a fringe of stable land suitable for coast-related activities (Anon 1993).

The descriptor *coastal* is more general as a term, and has a broader scope in that it includes the *coast* itself and the adjoining area in the marine environment and terrestrial environment that are proximal to the coast, sometimes merely proximal geographically, but other times with an environmental inter-relationship implied (*e.g.*, deposits stranded inland by progradation, but having been formed by earlier coastal sedimentation; or within the reach of wave splash or salt spray). For instance, *coastal* is defined by Bates & Jackson (1987) as pertaining to a coast, bordering a coast, or located at or near a coast, and *coastal area* as the area of land and sea bordering a shoreline. However, there is general disagreement on how far inland and how far seaward constitutes *coastal* (Anon 1995a, 1995b).

While *coast* as a term may be more or less defined in the scientific literature, in the area of coastal planning policy for administrative purposes, *coastal* is less precise, with different definitions generated by coastal managers in the various Local Governments based on administrative boundaries created for a specific demographic coastal location and the issues being addressed (Anon 1995a, 1995b). Here, "coastal", depending on author, may be narrowly defined, or so broad as to encompass a wide variety of Holocene shoreline, Holocene near-shoreline, prograded Holocene shoreline complexes (such as beach-ridge plains, *cf.* Searle *et al.* 1988; or prograded tidal flats *cf.* Semeniuk 1981a, 1982), and former Quaternary shoreline landforms. In the Standing Committee on Environment, Recreation and the Arts, in a report titled *The Injured Coastline: Protection of the Coastal Environment* to the Australian House of Representatives, it was argued that there were three main approaches to defining a coastal zone (Anon 1991b), these being 1. administrative (based, for instance, on administrative boundaries or offshore legislative boundaries, and clearly not scientific), 2. linear (based on arbitrary boundaries such as a linear reference point, and therefore mostly cadastral), and 3. biophysical (based on physical features such as a mountain range, or a natural ecosystem, and not necessarily related to the coastal zone but to other conspicuous boundaries or features). These approaches are conceptually and scientifically flawed.

In this paper, the term *coast* will be used to denote the modern strip separating land and sea, and generally occurring between high and low tide, and the term *coastal* will be used to denote a variety of environments that relate to the interaction between oceanic and terrestrial processes. As such, these will contain both land and ocean components, and have boundaries to the land and ocean that are determined by the degree of influence of the land on the ocean and the ocean on the land; and may not be of uniform width, height, or depth (Kay & Alder 1999). These environments may include, for example, the seaward margin of prograded coastal plains, or coastal dune belts (where they have been formed by coastal processes), or areas influenced by marine processes such as salt spray. Stranded sea cliffs, of Pleistocene age or earlier, are not included in this definition of coast.

In this context, the term *coastal geoheritage* is used to denote geoheritage aspects of the coastal zone, where the coastal zone is the shore, and where terrestrial and oceanic areas are, or have been, influenced by coastal processes.

As noted above, sites of geoheritage significance can include features that range in size from crystals to geological features at the scale of mountains and landscapes (Figure 2 of Brocx & Semeniuk 2007). This size gradation and processes/products at various scales also occur in the coastal zone, with geomorphic features ranging from micro-pinnacles (also termed "lapiés" by some authors; *cf.* Guilcher 1953; Paskoff 2005) and tafoni, to specific types of cliffs, to large coastal (depositional) systems such as deltas. Scale is formally addressed in terms of frames of reference of fixed sizes (Table 1), using regional, large, medium, small, and fine scales (after Semeniuk 1986), or megascale, macroscale, mesoscale, microscale, and leptoscale (after C A Semeniuk 1987).

Table 1

Scales of reference for geomorphic and geoheritage features

Frame of reference	**Descriptor**
100 km x 100 km or larger	regional scale (or megascale)
10 km x 10 km	large scale (or macroscale)
1 km x 1 km	medium scale (or mesoscale)
10–100 m x 10–100 m	small scale (or microscale)
1 m x 1 m, or smaller	fine scale (or leptoscale)

That is, the frame of reference is used to denote those features evident at that particular scale. For instance, cross-lamination, sedimentary layering, lamination, bubble sand, shell layers, tafoni and micro-pinnacles ("lapiés") are evident within a 1 m x 1 m frame of reference, while larger cliff faces, shoreline benches and sandy spits are evident within a 10 m x 10 m or 100 m x 100 m frame of reference.

How is the coastal zone different from other environments?

The coastal zone is a special environment because it is a dynamic zone of intersection and interaction of land, sea, groundwater, and atmosphere. As a result, the coastal zone carries with it an abundance of processes and products that are not present in other environments or only weakly developed in those other environments. For instance, in contrast to the shore environment, nearby marine environments adjoining the coastal zone, though graded with respect to depth (with its attendant effects on wave energy intersecting the shelf floor, sediments, and biota), tend to be more homogeneous environmentally because the oceanic milieu itself tends to be relatively more uniform, and generally removed from processes such as wind, or fresh-water discharge (Kuenen 1950; Shepard 1973; Berger 1974; Ginsburg & James 1974; Swift 1974; Wilson & Jordan 1983; Swift *et al.* 1984; Collins 1988). As such, the complexities of shore processes and products generally are absent in the adjoining shelf environment The shelf may be underlain by a relatively uniform sheet of sediment (or rock), while the adjoining coast will comprise a range of sediments (or morphologic types cut into rock) that reflect the gradient of the effects of waves, tides, wind, and hydrochemistry that impinge on or interact with the shore.

This is not to imply that the terrestrial environment cannot also be complex, but in the terrestrial environment geological complexity generally is manifest in two ways: firstly, in the inherent structural, lithological and mineralogic variability in the underlying materials (though their expression as parent material is often diminished by weathering); and secondly, in weathering itself, which produces soils that reflect hydrochemical and geochemical processes acting on these materials. In fact, soils and palaeosols, resulting from hydrochemical interactions on various parent rocks, can present some of the most complex structural and geochemical products in the terrestrial environment (Hunt 1972; Buol *et al.* 1973; Arnold 1983; FitzPatrick 1983; Leeper & Uren 1993), particularly since the processes may have been operating over millennia, and this has already been recognised elsewhere (Gauld *et al.* 2003). While soils can express complexity in the terrestrial environment, the geodiversity (if developed) is usually at the geochemical level and in terms of pedogenic structures. However, soils generally do not exhibit the range and scale of features that can be developed at the coast.

Leaving aside soils, the degree of complexity in landform, geology, mineralogy, and groundwater, under conditions of a prevailing climate, developed on and in the materials in the terrestrial environment, at their most complex geological and lithological expression, will express this degree of geological complexity at the coast, with the added factor that coastal physical, chemical and biological processes superimpose other features on them. Thus the geological and geomorphological units of the terrestrial environment generally become more complex where they interface with, or are transformed at their interface with the sea.

In regards to soils, in coastal situations, soils mostly are stripped away from rocks at the shore, but if still present, they can become involved in complex hydrochemical interactions at the coast (driven, for instance, by sea spray, and groundwater seepage).

As the interface between land and sea, the coastal zone is subjected to a range of physical, chemical and biological processes, often graded in intensity normal to the shore gradient. These are listed in Table 2 (information drawn from Johnson 1919; King 1972; Schwartz 1972, 1973, 1982, 2005; Ginsburg 1975;

Table 2

The main physical, chemical, and biological processes operating in coastal zones

- wave action, comprising swell of various periods, wind waves, and standing waves, resulting in a plethora of wave patterns and wave lengths, variable temporally and spatially, and variable normal to the shore in terms of translational waves, shoaling waves, and breaking waves, with their attendant effects of erosion, sediment mobility, particle size sorting, sedimentary structure development; this is a prevailing phenomenon at the shore;
- storm action, and associated storm surges, with their attendant effects of erosion, sediment mobility, particle size sorting, sedimentary structure development, amongst other effects; this is an episodic phenomenon at the shore;
- cyclone activity and associated surges, with their attendant effects of erosion, sediment mobility, sedimentary structure development, amongst other effects; this is an episodic phenomenon at the shore;
- tsunamis and seismic-related surges, with their attendant effects of erosion, sediment mobility, sedimentary structure development, amongst other effects; these are episodic phenomena at the shore;
- longshore drift with its attendant effects of sediment mobility and particle size sorting;
- rip currents with their attendant effects of sediment mobility, particle size sorting, and development of bedforms and sedimentary structures;
- development of a splash zone; this is a prevailing phenomenon at the shore;
- onshore winds, acting on the near-shore marine water body, resulting in shore-directed wind waves, longshore drift, and other currents, and seiches; these are commonly linked to seabreezes/landbreezes systems
- onshore winds acting on the upper shore face of sandy coasts, with their attendant effects of erosion, sediment transport, particle size sorting, lag development, and dune building;
- shore sedimentation physically mediated by river influx, longshore and/or onshore wave transport, and tidal currents;
- shore sedimentation biologically mediated by *in situ* or proximal skeletal production (mainly carbonate, but also siliceous);
- pronounced bioerosion;
- chemical erosion of susceptible minerals and materials;
- wetting and drying in the splash zone and the high-tidal zone;
- salt weathering, particularly in high tide zones, and splash zones;
- diurnal to semi-diurnal tidal inundation, and attendant tidal-current processes that result in erosion, sediment mobility, particle size sorting;
- diurnal to semi-diurnal invasion of coastal sedimentary bodies by seawater during high tide;
- evaporation of pore water and shallow groundwater in high-tidal zones during low tide and neap tides, driven by solar radiation and/or wind, to develop moisture gradients and salinity gradients, and hence biological gradients and geochemical gradients;
- transpiration, resulting in depletion of pore water and shallow groundwater in high tidal zones during low tide and neap tides to develop moisture gradients and salinity gradients;
- hydrochemical effects such as precipitation of calcium carbonate (aragonite or calcite), gypsum, or halite, where evaporation has markedly concentrated coastal groundwater and pore water;
- hydrochemical and geochemical effects such as solution;
- fresh-water seepage in the subsurface through appropriate aquifers into sandy coastal zones with its attendant effects of coastal erosion
- fresh-water seepage in the subsurface through appropriate aquifers into the coastal zone with its attendant effects on coastal ecology;
- fresh-water surface discharge onto the coastal zone;
- sediment delivery to the tidal zone by fresh-water discharge onto the coastal zone;
- flora habitation, and its material contribution, encrustations, and bioturbation;
- fauna habitation, and its attendant material contribution, encrustations, biostrome and bioherm building, and bioturbation (for discussion of biostromes and bioherms see Cummings 1932, Nelson *et al.* 1962, and Kershaw 1994)

Davidson-Arnott & Greenwood 1976; Klein 1976; Davies 1980; Bird & Schwartz 1983; Inden & Moore 1983; Greenwood & Davis 1984; Kelletat 1995; Black et al. 1998; Komar 1998; Woodroffe 2002; Semeniuk 2005).

Many of the processes listed in Table 2 are absent in the terrestrial environment. Those that do occur (*e.g.*, chemical erosion of susceptible rocks/materials, hydrochemical and geochemical effects such as precipitation of calcium carbonate, and hydrochemical and geochemical effects such as solution of specific minerals), particularly along the shores of lakes and playas, are more amplified in the coastal zone, or because there is interaction with seawater, the effects of the processes are manifested differently.

The significant feature to note from Table 2 is the prevailing nature of many of the interacting processes in the coastal zone, the short-term temporal variability of some processes (*e.g.*, Allen 1984 discusses the temporal variability of processes along the coastal zone), and those processes that are not present in other Earth environments (*viz.*, oceanic wave action, or daily tides, and seabreezes/landbreezes). Many of the processes are acting concurrently. Aquatic or wetland terrestrial environments (such as salt lakes and rivers) exhibit some of these processes resulting in complexity along their shores (particularly salt lakes because of their hydrochemistry) but generally not to the same degree as marine coastal zones. Further, the periodicity of some of the processes in coastal environments is generally not equivalent to terrestrial environments. Where there *is* similarity of periodicity, the processes are of a different nature. For instance, the annual effect of storms on a sand-and-mud coastal zone, temporally may be viewed as equivalent to the annual flooding of a sand-and-mud river system, but the actual processes and lithologies generated are markedly different.

To illustrate the added complexity a coastal setting provides in contrast to a partly-equivalent terrestrial system, the processes operating, and the geodiversity developed, in an inland dune system in an arid region is compared to dunes in a beach-dune coastal system. An inland dune system can be variable and complex at the medium scale down to lamination scale and grain-packing scale, with landforms, sedimentary structures, and grain packing varying in response to temporal changes in wind direction and wind intensity (resulting in laminae formed by grain fall, slip-face avalanche, traction, saltation, particle sorting, winnowing, rippling, and ripple-migration; Bagnold 1941; McKee 1979; Brookfield & Ahlbrandt 1983; Allen 1984). These dunes may be flanked by a geomorphically and lithologically distinct inter-dunal systems (usually of inter-dune flats; Glennie 1970; Kocurek 1981; Lancaster 1988). For coastal dunes, notwithstanding that they are commonly bordered after progradation by stranded dunes (which may undergo increasing diagenesis towards inland), and to seaward by a beach, such dunes essentially carry the same set of processes and develop the same set of sedimentary structural and grain-packing features as arid-region dunes, but have added complications with grain behaviour and grain packing as a result of their content of equant to platey carbonate grains and porous carbonate grains. Further, coastal dunes are bordered by a complex stratigraphy to seawards, in the environments encompassed by the nearshore, swash zone, berm, and foredune. As such, while the dunes themselves may be more or less comparable, the package of a coastal beach-dune system will show more geodiversity than dunes and inter-dune flats located in an arid region.

Another feature which sets the coastal zone apart from terrestrial environments is the extent of biological activity, such as skeletal production, trapping and binding in a sedimentologically dynamic system, boring, bioturbation, and mediation of diagenetic effects. Skeletal grain production can have an effect on sedimentation patterns regionally: with increased skeletal grain production, and sediments can change from siliciclastic to a siliciclastic-carbonate mixture to wholly carbonate in composition. Biogenic particle content may dominate over siliciclastic particle content at the local scale, or may dominate sedimentary patterns regionally. This latter situation is exemplified, for instance, by the carbonate sediments and reefs of Shark Bay, the west coast of the Persian Gulf, the Bahama Banks, Florida Banks, and the Great Barrier Reef (Davies G R 1970; Logan & Cebulski 1970; Logan *et al.* 1970; Purser 1973; Logan 1974; Bathurst 1975; Scholle *et al.* 1983; Tucker & Wright 1990). So while siliciclastic sediments and carbonate sediments can share common physical processes in the shore zone (*viz.*, wave action, tidal-current effects, aeolian effects, amongst others), and thus can generate the same suite of physical sedimentary structures such as layering, cross bedding, and ripple drift lamination, if biogenic processes and products become dominant, they add a specific signature to products. And while siliciclastic sediments (accumulating either in the coastal or terrestrial environments) can form environment-specific fine-scale to large-scale complex sequences in their own right, if biological effects begin to exert an influence, biogenic structures such burrows and bioturbation may become dominant.

While all the interactive processes that can operate on accumulations of siliciclastic sediments in the coastal and terrestrial environment are present in the carbonate coastal suite, there is the added factor in the carbonate sediment suite that carbonate minerals such as aragonite, Mg-calcite and calcite (because of their relative and differential solubility) may hydrochemically and biologically interact with the environment to a greater extent than do siliciclastic sediment particles, *i.e.*, carbonate sediments are more susceptible to diagenesis than siliciclastic sediments. For example, carbonate grains are susceptible to algal micro-boring and marine weathering, and there is a large range of diagenetic products developed in the tidal zone (Logan 1974; Bathurst 1975; Tucker & Bathurst 1990; Tucker & Wright 1990).

Additionally, coasts commonly exhibit gradients normal to shore, *e.g.*, a gradient in inundation and evaporation, with attendant gradients in wave energy and tidal energy, and hence a graded expression of processes of sedimentation, erosion, and hydrochemical effects. This results in variable, complex and diverse physical, geochemical and biological products across the shore, and variation in fine- to small-scale stratigraphic sequences. As a consequence, many of the processes listed in Table 2, operating in the coastal zone, result in a gradational array of products across the coastal gradients. Responses to a concentration gradient in hydrochemistry is an example: there is precipitation of carbonate minerals and gypsum from high neap tide and high spring tide to highest tidal level. The discharge of fresh water into the coastal zone, where it mixes with seawater, or concentrated seawater, also can result in a range of chemical gradients and products, such as precipitates, or in biologically-mediated chemical changes. The discharge of fresh water in the coastal zone, with a rise and fall of the water table, particularly along steep, sandy beach shores (Clarke & Eliot 1987; Horn 2002), can also result in the erosion and accretion of the shores, and in the diurnal development of shoreline beach cusps (Kuenen 1948; Mu 1958; Guza & Inman 1975; Werner & Fink 1993; Komar 1998; Coco *et al.* 1999; Short 1999), with their resulting complex meso- and micro-stratigraphy and sedimentary structures (Mii 1958).

Both sandy beaches and tidal flats exhibit stratigraphic and sedimentological complexity, with the degree of complexity to some extent related to climate and oceanographic setting (for instance, beaches in tropical climates can develop beach rock, and signatures of cyclone activity through development of beach-rock boulder ribbons; *cf.* Semeniuk 2008).

Sandy beaches provide excellent examples of the products of wave and tidal energy intersecting a sloping shore, and illustrate the range of sedimentary products that are developed across the slope gradient from shallow subtidal to supratidal, in response to the graded effect of waves, tides, wind and fresh-water seepage (Beall 1968; Clifton 1969; Clifton *et al.* 1971; Reineck & Singh 1971; Davidson-Arnott & Greenwood 1976; Semeniuk & Johnson 1982; Inden & Moore 1983; Allen 1984; Semeniuk 1997; and see later). For instance, wave action intersecting a sloping shore is translated to a lower flow regime (varying progressively upslope) to upper flow regime, and the resultant development of rippled beds, megarippled bedforms, and plane beds, respectively. Hourly, daily, weekly and seasonal variation in wave patterns, coupled with storm effects, tide fluctuation, and onshore winds, generates lamination, shell layers, cut-and-fill structures, discontinuities (Mii 1958; Panin 1967; Boothroyd 1969), variation in grain size across laminations, and bubble sand. Biological activity results in shell layers, burrows, and bioturbation.

Tidal flats generally provide a greater degree of stratigraphic and sedimentological complexity than beaches because often they are sedimentary environments wherein there is accumulation and interaction of mud, sand, gravel, and biogenic material (Semeniuk 2005), and so are used here to illustrate the sedimentological and stratigraphic intricacies that can be developed along the shore zone. Tidal flats may be muddy, sandy, gravelly, or covered in shell pavements, and compositionally they may be underlain by siliciclastic or carbonate sediments or their mixtures. Depending on climate, tidal level, substrate and salinity, tidal flats may be covered by salt marsh, mangroves, sea grass, algal mats, microbial mats, biofilms, as well as mussel beds, oyster beds and reefs, and worm-tube beds and reefs, and inhabited by a burrowing benthos of molluscs, polychaetes, and crustacea (Semeniuk 2005). Tidal flats are rich in processes and products resulting from oceanographic, sedimentological, geohydrological, hydrochemical, and biotic interactions (Klein 1963, 1976; Ginsburg 1975; Alexander *et al.* 1998; Black *et al.* 1998). As lower-energy systems, with less scope for physical reworking, they develop a profusion of natural history coastal features reflecting the products of daily tidal inundation, prevailing translating/shoaling waves, wind, evaporation, and biogenic reworking. For instance, there are the sedimentologic products of interactions between waves and tides (*e.g.*, cross-laminated sand, ripple-laminated sand, lenticular bedding, flazer bedding, laminated mud, ripple-laminated silt in clay), the products of interactions between sediments and biota (*e.g.*, various burrow forms zoned tidally across the shore, various types of root-structuring, skeletal remains related to tidal levels), the geomorphic products of tides (*e.g.*, tidal run-off on low-gradient slopes to form meandering tidal creeks), and the products of hydrochemical interactions with sediments (*e.g.*, dissolution of carbonate by acidic pore water; cemented crusts and their intraclast breccia derivatives; carbonate nodules; gypsum precipitates; and products of redox reactions such as biologically-mediated precipitation of iron sulphide). The tidal zone is so diagnostic that for stratigraphers and students of sedimentary rocks, identifying this environment in the geologic record is often an important first step in the reconstruction of palaeo-environments, the location of facies associated with coastlines, and the recognition of such markers in stratigraphic sequences in basin analyses (Semeniuk 2005).

At the next scale, the scale of meso-stratigraphic and larger, the stratigraphic products and geomorphic products of coasts are unique from another perspective: coasts interface with oceans, and oceans, as the receiving basins of solar radiation, can propagate to the shore their history *via* sea temperatures, wave climate and storms. They also can imprint on the shore their record of sea-level changes. With progradation, the coastal zone thus has the potential to register and preserve a variable, complex and fluctuating oceanic and climate history from erosional products, sedimentation products, geomorphology (*e.g.*, beach-ridge patterns and cheniers, amongst others), and fossil biota. Through the recognition of appropriate sea-level indicators (or markers), coastal-zone stratigraphy, coastal-zone geomorphology, progradational shores, and rocky shores also have the potential to preserve records of sea-level changes (for Western Australia, see Semeniuk 1985; Semeniuk & Searle 1986; Playford 1988; Semeniuk 1997; and Semeniuk 2008).

A selection of products specific to the coastal zone that particularly well illustrate the special nature of the shore is listed below in Table 3 in terms of stratigraphy, sedimentary structures, lithologic products, biogenic structures, and diagenesis.

In the context of Table 3, in order to provide a perspective of the diversity and complexity of sedimentary structures and fine- to small-scale stratigraphic sequences in the coastal zone compared to terrestrial environments and deeper water marine environments, a review of variety of text books and sedimentological references, that illustrate sedimentary structures and fine- to small-scale stratigraphic sequences

Table 3

Some products specific to the coastal zone

Stratigraphic products
Example 1: upward-shoaling sequence developed by a prograding sandy beach where an inclined shore interfaces, intersects and interacts with waves, tides, onshore winds and storms; this is one of the best developed of coastal stratigraphic sequences, as it brings into focus the interplay of coastal processes, sediments, biota, and hydrochemistry (Beall 1968; Clifton 1969; Clifton *et al.* 1971; Semeniuk & Johnson 1982; Inden & Moore 1983; Allen 1984; Semeniuk 1997); depending on climate and tidal range, the stratigraphic products can change latitudinally, *e.g.*, occurrence of beach rock and cyclone-generated sediments (Semeniuk 1996, 2008)
Example 2: upward-shoaling sequence developed by a prograding siliciclastic tidal flat that granulometrically grades from low-tidal sand, to muddy sand to high-tidal mangrove-vegetated mud; this sequence also is one of the best developed of coastal stratigraphic sequences, because it provides a plethora of sedimentary and stratigraphic products that are the result of a wide range of grain sizes, a stronger effect of the tides across tidal gradients, a stronger effect of biota because of the relatively lower energy setting, and the effects of hydrochemistry graded across the tidal flats; again (Thompson 1968; Ginsburg 1975; Semeniuk 1981a; Semeniuk 2005); depending on climate and tidal range, the stratigraphic products can change latitudinally, *e.g.*, occurrence of displacive gypsum and development of mangrove facies (Logan 1974; Brown & Woods 1974; Semeniuk 2005)
Example 3: upward-shoaling sequence developed by a prograding algal mat and stromatolites on a carbonate and evaporate tidal flat (Kendall & Skipwith 1969; Shinn *et al.* 1969; Logan *et al.* 1974)
Lithologic products
Example 1: beach rock conglomerate and breccia (Semeniuk 1996, 2008)
Example 2: shoreline coquina (Logan *et al.* 1970)
Example 3: intraclast breccia sheet (Hagan & Logan 1974; Logan 1974)
Sedimentary structures
Example 1: tidal flat sedimentary structures and layering such as bidirectional ripple cross-lamination, flazer bedding (Reineck & Singh 1980; Shinn 1983)
Example 2: flazer bedding (Reineck & Singh 1980)
Example 3: bubble sand within an upward-shoaling beach sand sequence (Emery 1945; Semeniuk & Johnson 1982; Inden & Moore 1983; Semeniuk 1997)
Biogenic structures
Example 1: U-shaped faunal burrows (Reineck & Singh 1980)
Example 2: stromatolitic layering and emergent structures showing smooth, tufted and pustular fabrics (Logan *et al.* 1974)
Example 3: lithophagic borings (Semeniuk & Johnson 1985)
Diagenetic products
Example 1: beach rock, cemented bands or layers (Ginsburg 1953; Semeniuk 1996, 2008)
Example 2: nodular gypsum replacing carbonate tidal flat sediments (Kendall & Skipwith 1969; Shinn 1983)
Example 3: precipitate aggregates forming nodules on shells or crustacean skeletons (Semeniuk 1981b)

from a diverse range of depositional systems was undertaken (Allen 1984; Bathurst 1975; Berger 1974; Bird & Schwartz 1985; Cas & Wright 1988; Collins 1988; Collinson & Thompson 1982; Cooke & Warren 1973; Conybeare & Crook 1968; Davies 1970; Davies 1980; Davis 1978, 1994; Davis & Ethington 1976; Duncan *et al.* 1992; Fisher & Smith 1991; Ginsburg 1975; Ginsburg & James 1974; Greenwood & Davis 1984; Hopley 1982; Inden & Moore 1983; Kelletat 1995; Kendall & Skipwith 1969; Klein 1976; Le Blanc 1976; Logan 1970, 1974; Matthews 1984; Middleton 1965; Morgan 1970; Pettijohn & Potter 1964; Potter *et al.* 1980; Purser 1973; Reading 1978; Reineck & Singh 1980; Rigby & Hamblin 1972; Scholle & Spearing 1982; Scholle *et al.* 1983; Semeniuk 1981a, 1996, 1997, 2008; Semeniuk & Johnson 1982, 1985; Shinn 1983; Shinn *et al.* 1969; Snead 1982; Swift 1974; Tillman & Siemers 1984; Tucker & Wright 1990; Walker 1979; Warme *et al.* 1981; Wilson & Jordan 1983). While

there is a degree of overlap, and some of the sedimentological and stratigraphic features dominant in coastal settings *can* occur in terrestrial sedimentary settings, though they are uncommon (*e.g.*, water escape structures, bubble sand, U-shaped burrows), the coastal environments provide the greatest diversity and complexity of physical, chemical and biological structures and products and environment-specific features. Bubble sand provides an illustration of this: bubble sand (as small trapped air pockets in sand) can occur in shoreline deposits adjoining lakes, and locally on sandy levees, but it is very uncommon. However, it is prevalent on coasts where there is wave action and a rising tide on a sandy beach – here it is a diagnostic feature of the upper-tidal zone of the beach (Semeniuk & Johnson 1982; Inden & Moore 1983; Semeniuk 1995).

The review showed that complexity, and development of environment-specific sedimentary structures and fine- to small-scale stratigraphic sequences are particularly evident biologically. This is because different areas of the Earth's coastal environments, depending on biodiversity (related to biogeography), climate, and type of coastal system, have varying coastal biota, and biota often form particular assemblages across the shore in response to gradients in wave energy, tidal level, salinity, substrate type, and grain size, amongst others (*e.g.*, mangroves in tropical muddy environments, saltmarsh in temperate muddy environments, mussel beds in low-tidal muddy environments). Some biota in specific settings develop coastal (tidal) biostromal or biohermal accumulations, for example, biostromal mussel beds (in The Wash and along the coast of North Wales, and the Wadden Sea; Yonge 1949; Evans 1965; Wolff 1983), or serpulid worm (biohermal) reefs (along the coasts in Eire, Scotland, and the Gulf of Mexico; Andrews 1964; Bosence 1973, 1979; Ten Hove & van den Hurk 1993).

To further illustrate the complexity of interacting processes and diversity of products that develop across a shore environment in contrast to terrestrial environments, several examples of sedimentary coastal systems and rocky-shore systems are described and compared below to (approximately) equivalent materials and sequences in terrestrial environments to contrast their geodiversity. For instance, upward-fining sequences involving sand and mud from a point bar is compared to an upward-fining sequence involving sand and mud from a tidal flat. In the range of comparisons provided, we have endeavoured to remain within the same climate setting as there has to be some measure of internal consistency in the environmental setting for comparisons to be meaningful.

It is this range of sedimentological, erosional, and diagenetic features, described above, and their strength of development that sets coastal geoheritage apart from continental (or inland) geoheritage.

Comparisons of the coastal zone with inland systems – a contrast of geodiversity

A range of rocks, sediment sequences, and lithologies occurring in the coastal zone are compared to terrestrial environments. Some of the comparisons are of directly equivalent rocks exposed in coastal and terrestrial environments. For sedimentary sequences, the comparisons are between coastal sediments and their stratigraphic sequences and sediments and stratigraphic sequences occurring in broadly lithologically similar materials in terrestrial environments. Comparison is also made with two other relatively complex environments, *viz.*, karst, and (active) volcanic terrains. The comparisons are intended to highlight the complexity and geodiversity of one environment in relation to the other. The examples are as follows (Figure 1):

1. a comparison between a fluvial ravine and a rocky shore, using the Tumblagooda Sandstone as the parent material;
2. a comparison between a natural inland cliff/ravine and a rocky shore, using a Pleistocene calcarenite as the parent material;
3. a comparison between an upward-shoaling stratigraphy of a point bar and an upward-shoaling tidal flat stratigraphy;
4. a comparison between the micro-stratigraphy of a mud-dominated floodplain and mud-and-sand floodplain and that of a mud-dominated tidal flat.

The multiplicity of interacting processes operating on a sandy beach and on a calcarenitic rocky shore is illustrated in Figures 2 and 3.

The Tumblagooda Sandstone exposed along the coastal rocky shores shows a wide variety of small-scale and fine-scale features not evident in the same Formation in fluvial ravine settings. Of particular importance is the effect of salt weathering in the coastal zone resulting in better exposure of lithology and sedimentary structures (Figures 1A–1D), the development of tafoni, structural benches (where bedding-plane features are well exposed), the wave-cut benches, pavements and slopes planed by marine processes, and the intertidal cementation. Structural benches exposing bedding-plane features on soft lithology such as shales, are recessively weathering in the fluvial ravines.

The contrast in geodiversity for Pleistocene calcarenites between natural inland cliff/ravines and the coastal zone is similar (Figures 1E–1H): the coastal exposures show more geodiversity than calcarenites occurring in inland exposures in terms of small-scale and fine-scale geomorphology, and in effects of coastal diagenesis. The coastal outcrops are also better exposed as a result of wave-washing, wind erosion, and salt weathering. The difference in geodiversity between a sedimentary sequence developed in an upward-shoaling tidal flat and that of an upward-shoaling stratigraphy of a point bar also is marked, with the former illustrating the products of intricate interaction between waves, tide, wind, and biota, and the latter showing a less developed assemblage of sedimentary structures and lithology (Figures 1E to 1H). The intricacies of physical, chemical and biological processes acting on tidal flats result in suites of lithologies, sedimentary structures and sedimentary products not developed in the point bar (Figures 1I–1J). In fact, the point bar, without a fluctuating floodwater level is a relatively simple stratigraphy and sequence of sedimentary structures. The final example, contrasting the micro-stratigraphy of a mud-dominated tidal flat with the micro-stratigraphy of a mud-dominated floodplain and a mud-and-sand floodplain shows, again, that the tidal-flat sequence in terms of sedimentary structures, lithology and biological effects is more complex and diverse, reflecting the interaction of particle sizes, tides, waves, inundation frequency, hydrochemical gradients, and biota (Figures 1K & 1L). Even though the scale of stratigraphy is somewhat different, the floodplain sequences show relative monotony of lithology, while the tidal flat mud sheet shows relative richness of features at the fine scale evident as lamination, burrows, burrow-mottling, flazer bedding, mud cracks and mud flakes.

Differences between coastal and terrestrial environments is well highlighted by contrasting a sandy beach system with fluvial sands. There is a marked difference in geodiversity between a sedimentary sequence developed under a beach in a microtidal setting, in terms of lithology, structures, and small-scale stratigraphy, in comparison to sand shoals in a sand-dominated river systems. As mentioned earlier, the beach sequences show the graded effect of waves, tide, wind, and biota on a sandy slope. There can be hourly, daily, weekly to seasonal adjustment of the beach profile in response to waves, the formation of beach cusps, and the cutting of cliffs in sand, as well as seasonal accumulation of storm deposits, amongst other effects, with the result there is a complicated layered and cross-layered stratigraphy, and scour-and-fill structures, bounded by discontinuities (Mii 1958; Panin 1967; Boothroyd 1969). Beach processes, sedimentology, and stratigraphy are summarised in Figure 2. In contrast, sand shoals in sand-dominated river systems exhibit a much less complicated sequence of laminated and cross-laminated sands. More complex stratigraphy in such systems occurs where there are lag concentrates of coarse sand and gravel, and where mud accumulates (and then dries and desiccates) in the troughs between megaripples and shoals.

In the examples presented above, the coastal zone manifests lithologically better exposed rocks and stratigraphic sequences, and sedimentologically more complex products and stratigraphy than the terrestrial environments.

This emphasis on the coastal zone is not intended to diminish geological complexity elsewhere. Other environments do have geodiversity, and it may be expressed in a variety of ways as will be illustrated by a brief synopsis of karst environments, volcanic settings, and landscapes developed by arid zone erosion.

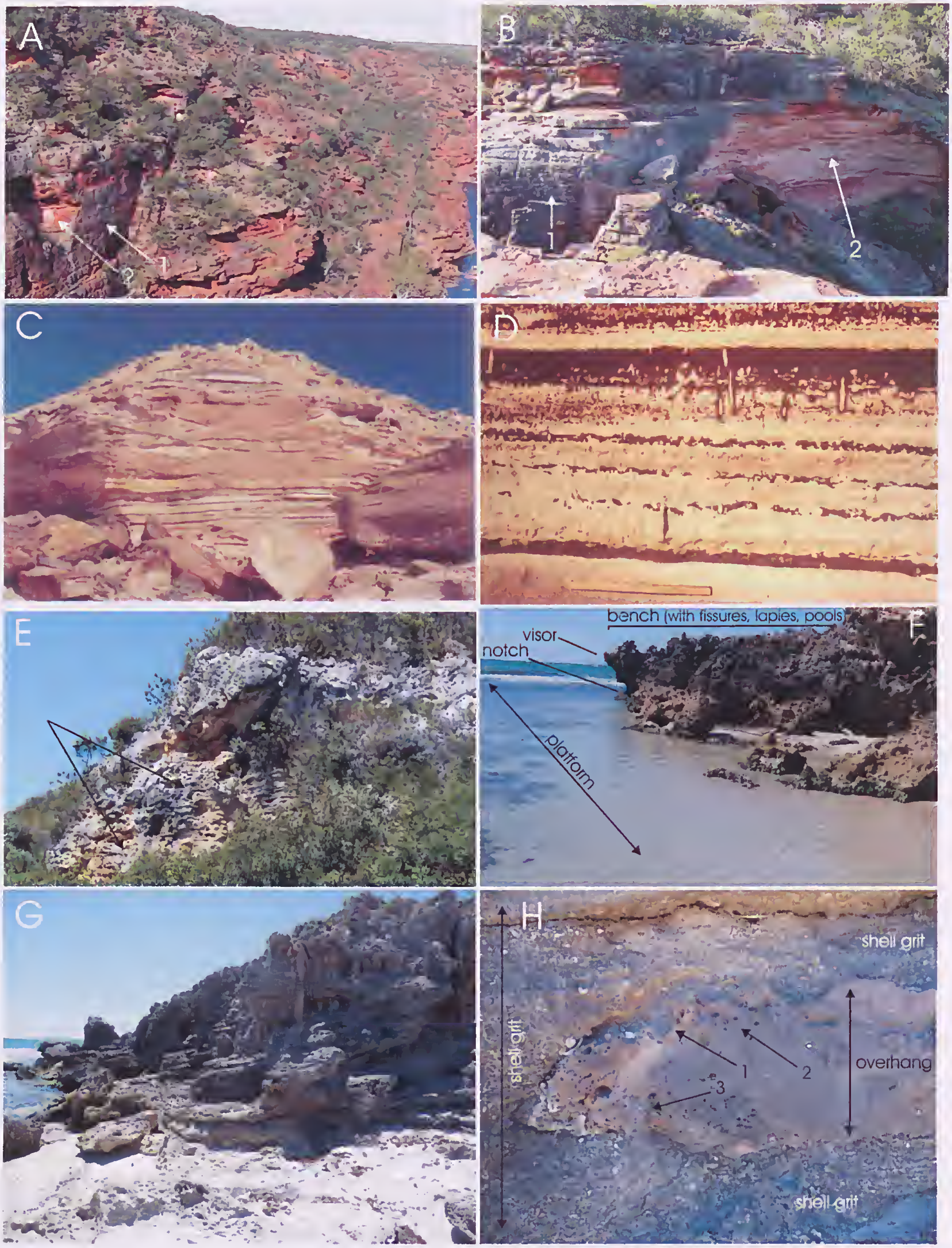
The karst environment, for instance, with its array of cave forms, sedimentology, and crystal development in drapes, sheets, curtains, stalactites and stalagmites, straws and helical structures, and the interlayering of crystal deposits and sediments is a complex and diverse environment, with diversity particularly expressed in the arrangement of crystal aggregates and their interaction with sedimentary fill (Cullingford 1953; Jennings 1971; Waltham 1974; Jakucs 1977; Gillieson 1996). Similarly, volcanic settings can be complex and (geo)diverse (Cas & Wright 1988; Fisher & Smith 1991). They may comprise variable magmas, lava-flow sheet and ribbon bodies and accompanying structures (*e.g.*, breccia, vesicules), the interactions between lava, water and atmosphere, the generation of ash, the interaction of volcanic products (such as ash) with rain, hot springs, magmatic waters and their mineralogic products, gas exhalations and their mineralogic products, and volcanogenic sedimentation, all of which result in a wealth of diverse geological features, from large scale to fine scale to mineral/crystal scale. Extinct volcanic terrains, with erosion, also generate a range of interesting and variable landscapes that are founded on the diversity of geological structures such as plugs, dykes, ash layering, and lava rivers, amongst others.

From the information above, it would seem that active volcanic settings could rival coastal settings for complexity and geodiversity, but while volcanic settings manifest a variety of products, coastal environments carry with them factors that add complexity beyond that developed in volcanic terrains. Coasts, as described above, generally manifest a greater geodiversity than some of other more complex terrestrial environments, including karst and volcanic environments, not only because the coastal zone is the "interaction zone" of a large number of processes, but also because, unlike other terrestrial systems, there is variation in processes temporally (at the scale of minutes, hours, days, weeks, months, and years), at the fine to small scale spatially, and latitudinally (regional scale spatially) which result in various expressions of coastal sedimentary deposits depending on terrigenous influx, climate, biodiversity, shelter, wave climate, tidal range, and coastal wind. For sedimentary bodies, for instance, in the shorter time frames, this can result in various expressions lithologically and at the scale of sedimentary structures: lamination and scour-and-fill in beach stratigraphy, responding to wave effects, and responding to the development and destruction of beach cusps, respectively, are the result of short-term temporal variation affecting sedimentary sequences on sandy coasts; flazer bedding in tidal flat stratigraphy responding to semi-diurnal tide and wave effects, is the result of temporal short-term variation affecting sedimentary sequences on tide-dominated, sand-and-mud coasts. For sedimentary bodies in the longer-term time frames, temporal changes in the coastal processes can result in changes in sedimentary style, stratigraphy, and sediment geometry.

Erosion of massifs in arid regions by wind, water, and salt-weathering also can result in locally well-exposed cliff faces to the same level of detail as in coastal cliff sections, particularly where wind erosion is involved. The stratigraphic sequences in Monument Valley, Arizona (USA), the Navajo Twins in Bluff Sandstone and other sandstone cliffs in south-east Utah (USA), the Ennedi Massif in the Sahara Desert (Chad, Africa), the Jebel Acacus in Libya (Africa), and ironstones exposed in the gorges of the Hamersley Ranges (Western Australia) exemplify this (Holmes 1966; MacLeod 1966; Cooke & Warren 1973; Oberlander 1977; Schlüter 2005).

Discussion

Geoconservation is concerned with the protection and management of geological sites for the preservation of special outcrops, palaeontological, mineral, and pedological localities, geoarchives that represent a page from the Earth's history, locations where Earth processes are active, locations that are representative of the Earth's


A
2
1
B
1
2
C
D
E
bench (with fissures, lapies, pools)
visor
notch
platform
F
G
H
shell grit
shell grit
1
2
3
overhang
shell grit

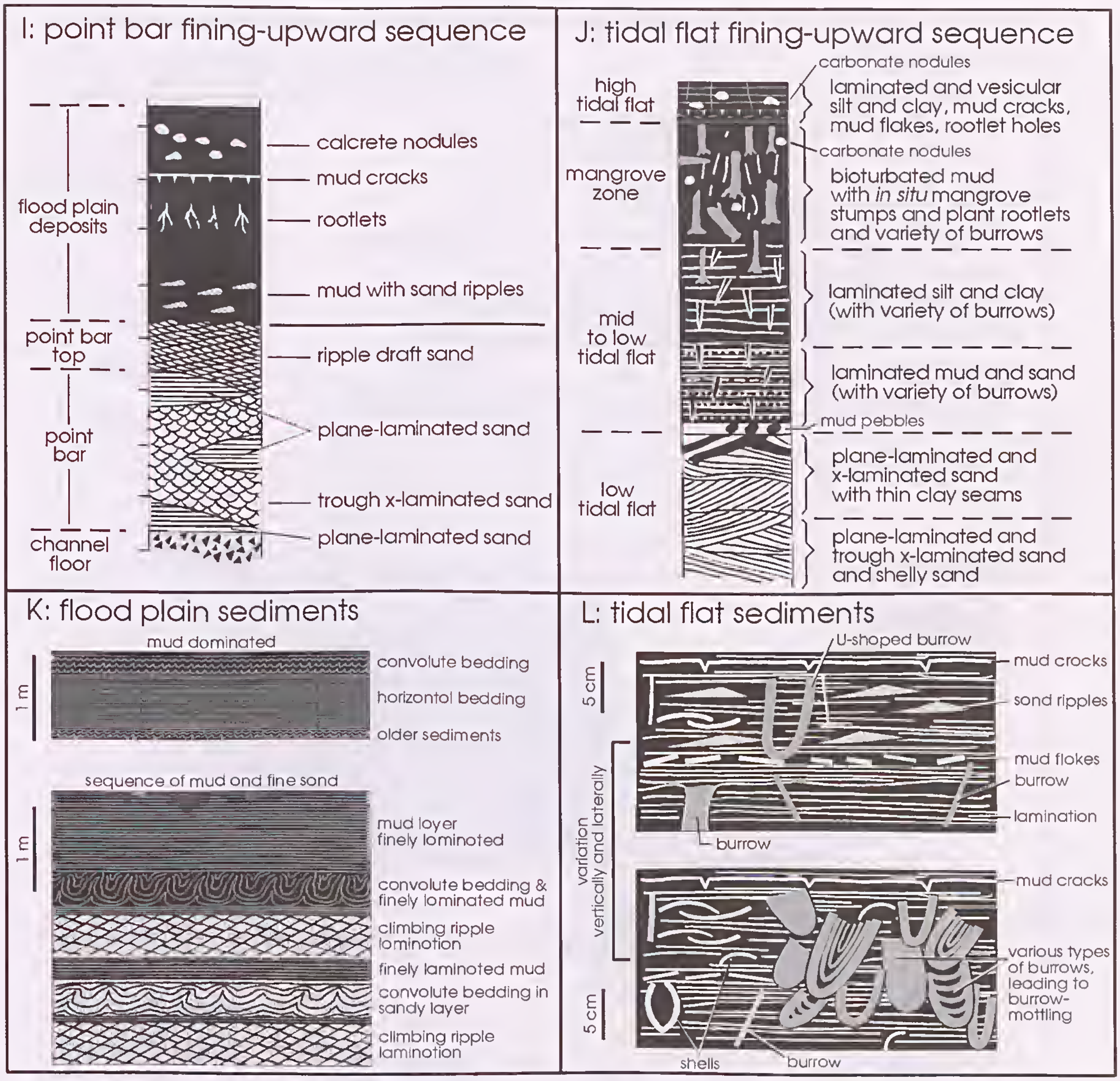

I: point bar fining-upward sequence
flood plain deposits
point bar top
point bar
channel floor
calcrete nodules
mud cracks
rootlets
mud with sand ripples
ripple draft sand
plane-laminated sand
trough x-laminated sand
plane-laminated sand
J: tidal flat fining-upward sequence
high tidal flat
mangrove zone
mid to low tidal flat
low tidal flat
carbonate nodules
laminated and vesicular silt and clay, mud cracks, mud flakes, rootlet holes
carbonate nodules
bioturbated mud with in situ mangrove stumps and plant rootlets and variety of burrows
laminated silt and clay (with variety of burrows)
laminated mud and sand (with variety of burrows)
mud pebbles
plane-laminated and x-laminated sand with thin clay seams
plane-laminated and trough x-laminated sand and shelly sand
K: flood plain sediments
mud dominated
1 m
convolute bedding
horizontol bedding
older sediments
sequence of mud ond fine sond
1 m
mud loyer finely lominoted
convolute bedding & finely lominated mud
climbing ripple lominotion
finely laminoted mud
convolute bedding in sandy layer
climbing ripple lominotion
L: tidal flat sediments
5 cm
U-shoped burrow
mud cracks
sond ripples
mud flokes
burrow
lamination
burrow
variation vertically and laterally
mud cracks
various types of burrows, leading to burrow-mottling
5 cm
shells
burrow

Figure 1. Contrast between terrestrial and coastal geodiversity. A–D. Outcrops of the Tumblagooda Sandstone. A & B. Outcrop of the Tumblagooda Sandstone in Murchison River gorge near Kalbarri. The walls of the gorge do not expose well the lithological and structural details of the Formation, in that joint-controlled vertical cliffs usually are iron oxide coated (1), and the general outcrop is weathered. Recent rock falls exposed weathered rock (2). C. Wave-washed, wind-eroded, and salt-weathered cliff face of the Tumblagooda Sandstone at Red Bluff, Kalbarri showing well exposed lithological and structural features. A large channel-form is clearly evident in the cliff, and layering is prominent and traceable. D. Close-up of (C) showing lithological and structural details of trace fossils and layering (scale is 30 cm). E–H. Outcrops of Pleistocene calcarenites. E. Outcrop of calcarenite along a natural cliff several kilometres from the coast, showing crusted surface, and poor exposure of lithological and structural features. Some lamination is arrowed. The base of the cliff is covered in sand (as fans) and breccia. F. Coastal exposure of calcarenite in the Perth area, showing range of geomorphic features (platform, notch, visor, bench with micro-pinnacles or lapiés) developed as a result of shore erosion and solution of Pleistocene calcarenite at North Beach, Western Australia. G. Rocky shore exposure of calcarenite at Muderup Rocks (Cottesloe, Western Australia) showing well exposed stratigraphic, structural and lithological features brought out by wave erosion, salt weathering and wind erosion, *viz.*, prominent lamination and cross-lamination. H. Rocky shore exposure of calcarenite at Muderup Rocks showing well exposed laminated shell grit (arrowed interval), unconformably overlying (and underlying) a rocky shore overhang in older calcarenite; the overhang is hard band, bored by echinoids (1), pholadids (2), and other lithophagic organisms (3); see Semeniuk & Johnson (1985). I & J. Contrasting upward-fining sedimentary sequences of a terrestrial system (a point bar) and a coastal system (a tidal flat). I. Point bar stratigraphy showing structures in sand, fining up to a mud sequence (modified after Walker 1979). J. Tidal flat stratigraphy showing structures in sand, in the interlayered mud and sand, and in mud (modified after Semeniuk 1981a). K & L. Contrasting the details of a mud sheet and a mud-and-sand sheet formed in a terrestrial system (a floodplain) with that of a mud sheet formed on a tidal flat. Note that the structures and lithology of the floodplain sediments are expressed over an interval of a metre or more, while the intricate details of structures in the mud of a tidal flat occur within an interval ~ 20 cm. The comparison is intended to contrast the relative monotony of a floodplain sequence with the relative richness of features evident in tidal flat mud deposits. K. Details of structures of the mud sheet and a mud-and-sand sheet formed on a floodplain (information adapted from McKee 1966; McKee *et al.* 1967; Walker 1979 and Potter *et al.* 1980). L. Details of structures of a mud sheet formed on a tidal flat (information adapted from Reineck & Singh 1980 and Semeniuk 1981a, 2005).

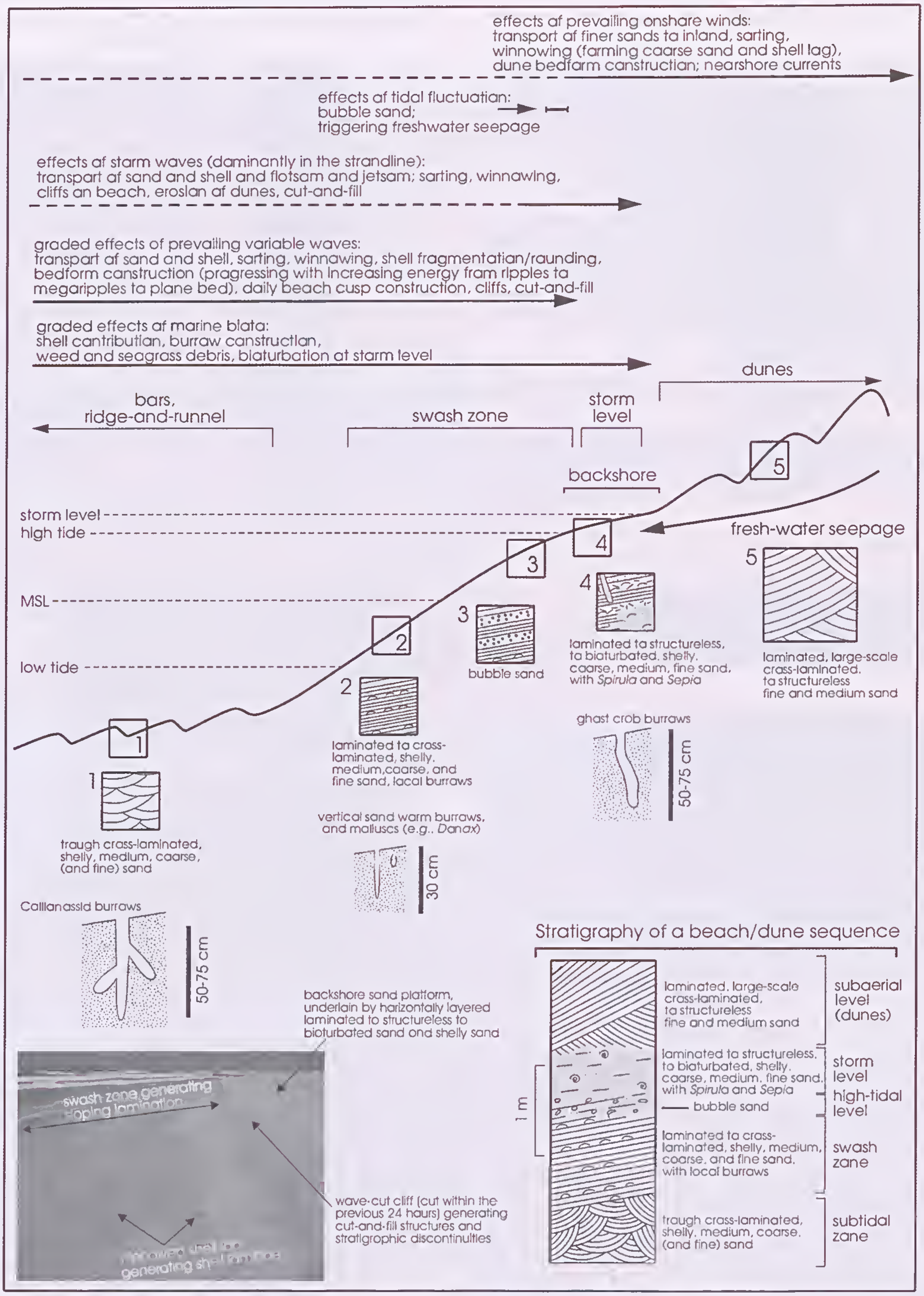

effects of prevailing onshore winds:
transport of finer sands to inland, sorting, winnowing (forming coarse sand and shell lag), dune bedform construction; nearshore currents
effects of tidal fluctuation:
bubble sand;
triggering freshwater seepage
effects of storm waves (dominantly in the strandline):
transport of sand and shell and flotsam and jetsam; sorting, winnowing, cliffs on beach, erosion of dunes, cut-and-fill
graded effects of prevailing variable waves:
transport of sand and shell, sorting, winnowing, shell fragmentation/rounding, bedform construction (progressing with increasing energy from ripples to megaripples to plane bed), daily beach cusp construction, cliffs, cut-and-fill
graded effects of marine biota:
shell contribution, burrow construction, weed and seagrass debris, bioturbation at storm level
dunes
bars, ridge-and-runnel
swash zone
storm level
backshore
storm level
high tide
MSL
low tide
fresh-water seepage
1
2
3
4
5
trough cross-laminated, shelly, medium, coarse, (and fine) sand
laminated to cross-laminated, shelly, medium,coarse, and fine sand, local burrows
bubble sand
laminated to structureless, to bioturbated, shelly, coarse, medium, fine sand, with Spirula and Sepia
laminated, large-scale cross-laminated, to structureless fine and medium sand
Callianassid burrows
50-75 cm
vertical sand worm burrows, and molluscs (e.g., Donax)
30 cm
ghost crab burrows
50-75 cm
backshore sand platform, underlain by horizontally layered laminated to structureless to bioturbated sand and shelly sand
swash zone generating sloping lamination
wave-cut cliff (cut within the previous 24 hours) generating cut-and-fill structures and stratigraphic discontinuities
Stratigraphy of a beach/dune sequence
1 m
laminated, large-scale cross-laminated, to structureless fine and medium sand
subaerial level (dunes)
laminated to structureless, to bioturbated, shelly, coarse, medium, fine sand, with Spirula and Sepia
storm level
bubble sand
high-tidal level
laminated to cross-laminated, shelly, medium, coarse, and fine sand, with local burrows
swash zone
trough cross-laminated, shelly, medium, coarse, (and fine) sand
subtidal zone

Figure 2. Processes and products on a sandy beach (graded across the beach). Waves, tides, wind, fresh-water seepage, and biota interact with a sloping sandy shore producing a range of sedimentary products related to the slope gradient (information from Mii 1958; Panin 1967; Beall 1968; Boothroyd 1969; Clifton 1969; Clifton *et al.* 1971; Reineck & Singh 1971; Davidson-Arnott & Greenwood 1976; Semeniuk & Johnson 1982; Inden & Moore 1983; Allen 1984; Semeniuk 1997). The stratigraphy generated by lateral progradation and shoaling of the beach is also shown. The photographic inset shows the surface of a beach: selected geomorphic and sediment units of the beach are noted, with description of the types of sediments and structures that underlie them. The sand cliff marking the edge of the berm was cut within the previous 24 hours of the photography.

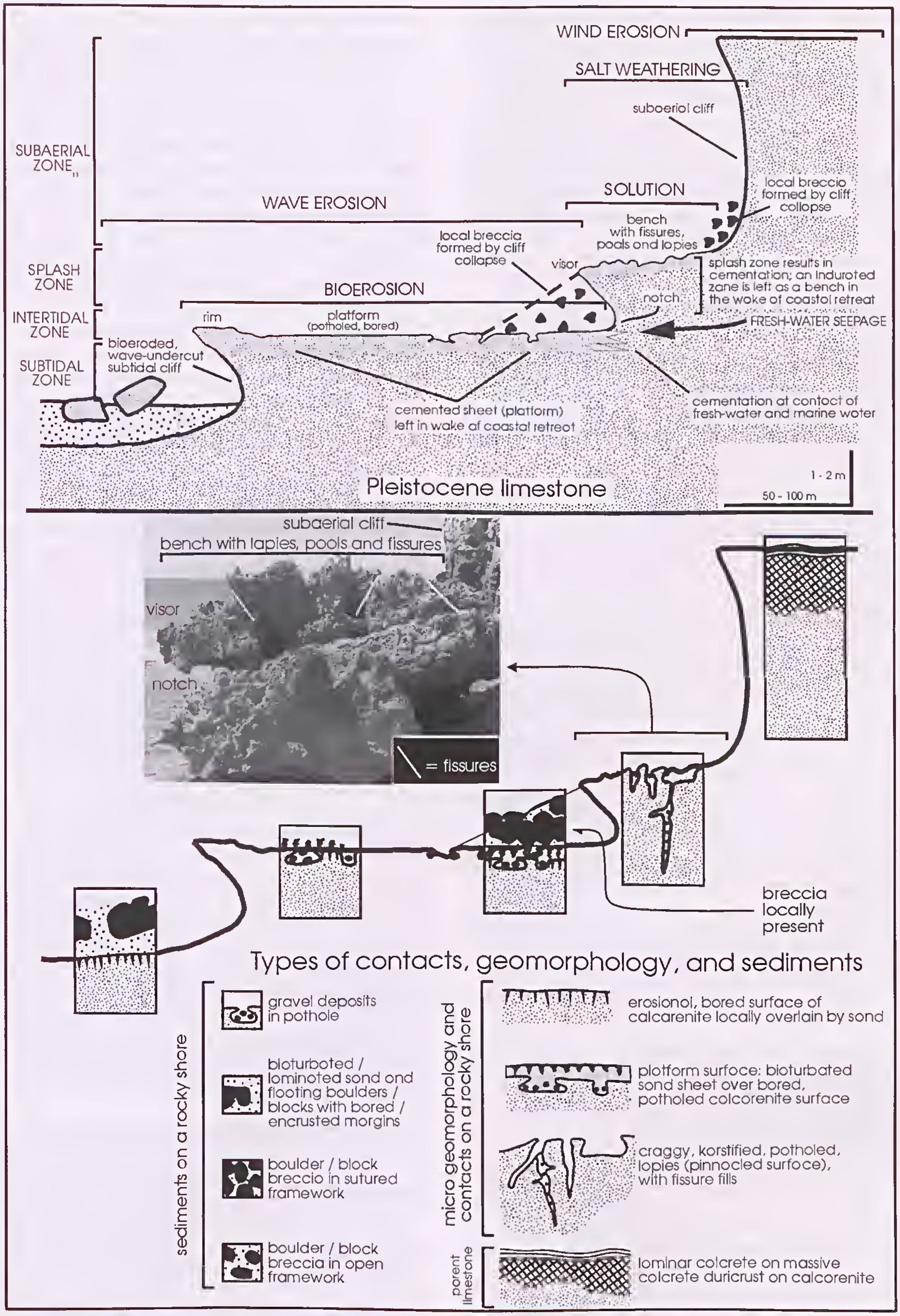

WIND EROSION
SALT WEATHERING
subaerial cliff
SUBAERIAL ZONE
SOLUTION
local breccia formed by cliff collapse
WAVE EROSION
bench with fissures, pools and lapies
local breccia formed by cliff collapse
visor
SPLASH ZONE
splash zone results in cementation; an indurated zone is left as a bench in the wake of coastal retreat
BIOEROSION
notch
INTERTIDAL ZONE
rim
platform (potholed, bored)
FRESH-WATER SEEPAGE
bioeroded, wave-undercut subtidal cliff
SUBTIDAL ZONE
cemented sheet (platform) left in wake of coastal retreat
cementation at contact of fresh-water and marine water
1 - 2 m
50 - 100 m
Pleistocene limestone
subaerial cliff
bench with lapies, pools and fissures
visor
notch
= fissures
breccia locally present
Types of contacts, geomorphology, and sediments
sediments on a rocky shore
gravel deposits in pothole
bioturbated / laminated sand and floating boulders / blocks with bored / encrusted margins
boulder / block breccia in sutured framework
boulder / block breccia in open framework
micro geomorphology and contacts on a rocky shore
erosional, bored surface of calcarenite locally overlain by sand
platform surface: bioturbated sand sheet over bored, potholed calcarenite surface
craggy, karstified, potholed, lapies (pinnacled surface), with fissure fills
parent limestone
laminar calcrete on massive calcrete duricrust on calcarenite

Figure 3. Processes and products on a rocky shore cut into Pleistocene calcarenite. Waves, tides, wind, fresh-water seepage, and biota interact with and have modified the calcarenite geomorphically, chemically, mineralogically and biologically (information from Wentworth 1938; Edwards 1941; Emery 1945; Hills 1949; Fairbridge 1950; Guilcher 1953; Emery & Foster 1956; Emery & Kuhn 1956; Bird & Dent 1966; Semeniuk & Johnson 1985; Stephenson 2000). The small-scale stratigraphy and geomorphic features at various levels along the rocky shore, generated by erosion, sedimentation, and biota, are also shown: The photographic inset shows details of the notch, visor, and the craggy nature of the bench (with lapiés, pools, and fissures).

geodiversity, and sites that are of cultural significance (Sharples 1995; Barettino *et al*. 1999; Brocx & Semeniuk 2007; Brocx 2008; Erikstad 2008). The coastal zone is especially significant in a context of geoconservation because, as emphasised in this paper, of all the environments on the Earth's surface, it is one of the most complex in terms of landforms developed, sedimentological processes and products, and diagenetic processes and products, manifesting high geodiversity of Holocene landforms, stratigraphy, sedimentology, and diagenesis. It also exposes some of the best and most detailed outcrops (globally, including Western Australia) where geological history can be readily investigated. Such exposures have the potential for high geoheritage significance, and indeed some cliff exposures already have been afforded global and national geoheritage significance either because of their geological importance (the cliffs in Dorset and East Devon, and along the Sussex coast in the United Kingdom), or because of their cultural importance (the unconformity at Siccar Point, Scotland).

As a result of the interactions between the various processes, and between processes and products along the shore compared to terrestrial environments and submarine environments, a large range of physical, chemical, structural, and biological features and environment-specific features occur in the coastal zone. In addition to the complexity of forms, the interactions of land, sea, groundwater and atmosphere along the coastal zone, occurring at all scales, result in a grade in sizes of many of the coastal products. For sedimentary bodies, this ranges from the (larger-scale) geometric forms of sedimentary deposits down to the scale of laminae and grains. For eroding rock sequences, this ranges from cliffs to benches to tafoni and micro-pinnacles ("lapiés") to structures and grains etched out in relief.

As such, the coastal zone is an environment where there should be a focus on geoconservation.

As noted earlier, the emphasis on the geodiversity of the coastal zone in this paper is not intended to diminish the importance of geological complexity elsewhere, but rather to point out the geological richness of natural features developed along the coastal zone, the nature of coastal outcrops compared to inland sites, and to provide some explanation of why the coastal zone displays geodiversity to the extent that it does.

In this paper we have highlighted the reasons that the coastal zone generally has greater geodiversity in terms of geomorphology, sedimentology, and diagenesis than some of the other complex environments: because it is the "interaction zone" of a large number of marine, terrestrial, groundwater and atmospheric processes, and because, in contrast to terrestrial, marine and volcanic systems, there is variation of geological processes and products temporally and spatially, with the variation depending on the coastal setting, the extent of terrigenous influx, climate, biodiversity, shelter, wave climate, tidal range, and coastal wind.

Temporal variation occurs in the time-frames of minutes, hours, days, weeks, months, and years for the processes involving waves, tides, winds, storms, cyclones, and fresh-water discharge. For sedimentary bodies, in short-term time frames, this can result in various expressions lithologically, and at the finer scales, in diverse sedimentary structures. In long-term time frames, this can result in changes in sedimentary style, stratigraphy, and sediment body geometry. Laminae in sand in the swash zone of beaches, varying in grain sizes or grain packing, can be reflecting variation in transport, winnowing, or grain-size sorting under the effect of waves and currents fluctuating in intensity in time frames of minutes or less. Annual storms, or cyclones returning perhaps on a decadal basis, can result in larger-scale sedimentological and stratigraphic responses such as the development of major scours and cliffs, development of shoreline spits, emplacement of gravel sheets and bars, or development of shell pavements by winnowing processes.

Spatial variation is from fine to small scales to regional scale (latitudinally). At fine to small scales, this may be expressed in shore-normal gradients in wave energy, tides, and hydrochemistry, that result in variation in geodiversity across the shore. Variation upslope in lithology, bedforms, and sedimentary structures reflect gradients in wave and tidal energy. Variation upslope in types of precipitates reflect gradients in hydrochemistry. At regional scales, spatial variability can be expressed in latitudinal (climatic) and environmental gradients, with other factors such as riverine influx and hinterland geology being equal. For instance, in Western Australia, latitudinal (climatic) gradients are expressed in the variation in landforms, coastal erosion, and diagenesis of Pleistocene calcarenites from their most southern occurrence along the Leeuwin-Naturaliste Ridge to their outcrop along the Zuytdorp Cliffs, a distance of over 1000 km. The variation within the Quindalup Dunes of Holocene coastal dune forms, landform assemblages, sediment types and their diagenesis, from their most southern occurrence in Geographe Bay to their most northern occurrence at Dongara (Semeniuk *et al*. 1989), is another example of differences expressed along a latitudinal (climatic) gradient. Changes in style of development of parabolic dunes serve as an example. Within this belt of Quindalup Dunes, Semeniuk *et al*. (1989) show that along the climate gradient, with change in wind direction and wind intensity, the coastal parabolic dunes change from short-axis easterly-ingressing generally simple and relatively small parabolic dunes in southern areas of the Swan Coastal Plain, to short-axis northeasterly-ingressing fretted larger parabolic dunes in central areas of the Swan Coastal Plain, to long-axis northerly-ingressing markedly attenuated (hairpin) and linearly extensive parabolic dunes in northern areas.

At the most fundamental level, leaving aside biogenic input, the coast modifies the hinterland by interacting with it. Being a "ribbon" environment, or viewed globally, a relatively thin "linear" environment, the coast traverses topography, variable geology and structures, oceanographic settings, climate of the coast and climate of the hinterland, tidal ranges, biogeography, and sedimentary style (*e.g*., delta-dominated, or barrier-dominated, or carbonate sediment dominated, amongst others). The coast is the most widespread linear environment on Earth. By definition it is circumferential to all landmasses facing the marine environment and thus inherently holds the largest potential to be the most variable environmental interface on Earth. And therein lies the reason for its geodiversity, and why coastal geoheritage within the umbrella of geoheritage has been emphasised in this paper. By way of contrast, volcanic systems, which earlier in this paper are recognised as having characteristics of high geodiversity, are not so consistently interconnected, even if portrayed as being in a "ring of fire" (*e.g.*, the "Pacific ring of fire"; Sutherland 1995; Murphy & Nance 1998). They tend to create their own volcanic environment and its environmental subsets, and create their own range of products from magma interacting with bedrock geology, water and atmosphere. While exhibiting high geodiversity at the local scale, at the global scale volcanic systems tend to be "nodal".

An outcome of the effect of erosion in the coastal environment is that coasts generally provide excellent locations for studying rock sequences (sedimentary, igneous, or metamorphic). Fine- to small-scale rock structural features, intra-lithologic features, and various lithologic types are brought out best by coastal erosion effected by wave washing, (sand-charged) wave erosion, wind erosion, and salt weathering. A corollary is that the exposures along the coast are often also the best outcrops for type sections and reference locations. The chalk cliffs of the southern coast of the United Kingdom, the stratigraphy exposed along the coast of Devonshire in the United Kingdom, the unconformity at Siccar Point in Scotland, and in Western Australia, the Tumblagooda Sandstone at Kalbarri, the Broome Sandstone at Gantheaume Point, and the Toolinna Limestone along the edge of the Nullarbor Plains, exemplify this.

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Bushfire history from grasstrees at Eneabba, Western Australia

D J Ward

2a Dreyer Road, Roleystone, WA 6111
✉ mumpnpop@iinet.net.au

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Abstract

A method for reconstructing bushfire history from fire marks on grasstree stems (*Xanthorrhoea* species) has been suggested for south-western Australia. Depending on the grasstree age, the history can extend back for over two centuries. Such history is important in understanding the behaviour of bushfires and their effect on ecology; in managing them to protect people and their assets; and for nature conservation. Two critiques of the grasstree method have been published, based on its application in *kwongan* heath, a few hundred kilometres north of Perth. Both papers extrapolate their criticism to previous grasstree work in vegetation south of Perth, such as the *jarrah* forest. This paper addresses the second paper, dealing with *kwongan* data from Eneabba. I show that the pattern of agreement between fire intervals derived from grasstrees and satellite images, over a thirty year period, is unlikely to occur by chance. Data from grasstrees dating back to the 1920s show a clear lengthening of fire intervals over the twentieth century. Reasons for disagreement between grasstree and satellite data are discussed. These include the omission of some grasstree data, possible errors in grasstree interpretation, and possible errors in satellite image interpretation.

Keywords: bushfire, history, *kwongan*, grasstree, satellite, Eneabba, Western Australia, *Xanthorrhoea*

Introduction

A method for reconstructing bushfire history from fire marks on grasstree stems (*Xanthorrhoea* species) has been suggested, based on considerable sampling (over 500 stems) in dry woodlands and forests of south-western Australia (Ward 1996; Ward & Van Didden 1998; Ward *et al.* 1998; Lamont *et al.* 1999; Lamont & Ward 1999; Ward & Challinor 1999). The occurrence of past fires is shown by black marks on grasstree stems. These black marks, and intermediate vertical growth rings, are revealed by cleaning the charcoal from the stems. Chemical and histological work has confirmed that the black marks are caused by naphthoquinone, trapped in the vascular system of the needles by their sudden death (Colangelo *et al.* 2002). The most likely cause of such sudden death is bushfire.

With some grasstree records stretching back to before European settlement, the grasstree work has suggested consistently high bushfire frequency (2–4 year return period) generally prior to the 1930s, in dry *jarrah* (*Eucalyptus marginata*) and *tuart* forests (*Eucalyptus gomphocephala*), and in various woodlands (*Eucalyptus wandoo, Melaleuca* spp. and *Banksia* spp.).

These short fire intervals closely match those reported by early settlers and officials (Drummond 1844, Harris 1882, Hutchins 1916, Lane-Poole 1921, Bunbury & Morell 1930, Stoate & Helms 1938, Wallace 1966, Hallam 1975, 1985, 2002, Ward 1997, Abbott 2003, Hunt 2006), and given by members of the current *Nyoongar* (Aboriginal) community (Eades 1999, Wilkes 2006, Hume 2006). They also match the implications of bushfire behaviour drawn from some mathematical modelling using Percolation Theory. Patchy burning of between a quarter and a third of an area each year prevents broad fire fronts developing (Loehle 2004).

An understanding of history, in particular past human activities, is essential to ecology at the landscape scale (Naveh & Lieberman 1994; Swetnam *et al.* 1999; Burel & Baudry 2003). Some authors correctly point out problems with historical approaches (*e.g.* Miller *et al.* 2007), but this does not mean that all history should be discarded. Problems can arise with statistical approaches to ecology, but this does not mean that one should discard all statistics. Drawing on philosophy, the word consilience (Whewell 1840) comes to mind. It means a 'jumping together' of inductive evidence from a range of independent sources. There has been a call for greater recognition of the importance of consilience, in that scientists need, in their models and theories, the four qualities of parsimony, generality, consilience, and predictive ability (Wilson 1998).

Since its first publication (Ward 1996), there has been some questioning of the validity of the grasstree technique. Some of these criticisms have been in the political arena, so lie outside the scope of this journal. Other critics are research workers (Enright *et al.* 2005; Miller *et al.* 2007), who are concerned because fire histories reconstructed from grasstree stems contradict previous estimates of past fire intervals, derived from a seedbank model (Enright *et al.* 1998), or estimates of bushfire dates derived from satellite images. In this paper I focus on one of the critiques (Miller *et al.* 2007). Brief comment has already been made on the other (Ward 2006).

Miller *et al* (2007) (from here also referred to as 'the authors') compared the fire dates derived from grasstrees

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in *kwongan* heath at Beekeepers' Reserve, Eneabba, over a thirty year period (1973–2002 inclusive), against their interpretation of satellite photographs taken over the same site on clear days in August/September. From these data, they concluded that the fire dates derived from grasstrees showed little better than random association with those derived from satellite images, and are therefore unreliable. Miller *et al* (2007) cautioned against applying grasstree interpretation as an aid to bushfire management. Without further satellite interpretation, Miller *et al* (2007) extrapolated that caution to the more southerly vegetation, such as *jarrah* forest, sampled in previous grasstree work (Ward 1996; Ward & Van Didden 1998). They suggested that some past fire intervals, estimated from grasstrees, are too short for the survival of some plants. Miller *et al* (2007) also claimed that *kwongan* heath does not accumulate enough fuel to carry fire at the short intervals (3–5 years) often shown by the grasstrees. This paper examines these criticisms, and arrives at other conclusions.

Methods

As a first step, the raw data used by Miller *et al* (2007) were carefully checked against copies of the field sheets. Where found, errors and omissions were corrected.

Secondly, the logic used by Miller *et al* (2007) in defining agreement between fire dates derived from grasstrees, and those derived from satellite images, was evaluated. The authors, in their main contingency tables [Table 2 of Miller *et al* (2007), which uses the term 'confusion matrix'] only allow agreement when the grasstree and the satellite data show exactly the same calendar year. In this paper a different reasoning is used.

Satellite images taken in August/September will show, as new fires, those that occurred since the previous August/September, a period which straddles two calendar years. Miller *et al* (2007) note this, but do not use it in their reasoning. In *kwongan*, fires are now more likely in summer, but can occur at any time of year. For example, a fire first noted on a satellite image in calendar year 2000, may have occurred in 2000, or in 1999.

Similarly, due to the fire season straddling two calendar years, if a fire shown on a grasstree stem is dated as, say, 2000, this means it could have occurred in the fire season 1999/2000, or 2000/2001. Based on this reasoning, in this study, grasstree fire dates were allowed a tolerance of a calendar year either way, and fires dated from satellite images a year's extension backwards. Contingency tables were created using these wider, and more reasonable, tolerances for agreement.

Satellite images, due to resolution problems, will consistently fail to show very small fires (Price *et al.* 2003). In Beekeepers' Reserve, at Eneabba, such small fires could occur on individual grasstrees, or small groups, especially in winter, due to ignition by beekeepers, or wildflower pickers, or kangaroo shooters. Miller *et al* (2007) do concede the 'possibility of some error' in the satellite fire record, including the failure to show individual grasstree ignitions, but then use the satellite record as the benchmark 'truth'. In this paper I make no prior assumption on 'truth'. Hence, the terms 'agreement' and 'disagreement' are used when comparing grasstree fire records with those interpreted from satellite imagery, rather than the authors' terms 'true-positive, false-negative' *etc.*, which give a misleading air of certainty to the fire dates derived from satellite images.

Thirdly, a statistical method used by Miller *et al* (2007) was reviewed. The authors subjected their 'confusion matrices' to analysis using the κ (kappa) statistic (Galton 1892; Cohen 1960; Landis & Koch 1977). This seems to be a technique commonly used in the educational, psychological, and medical fields, but is a weak statistic, in that its sampling distribution is unknown, so one can never be sure of the significance of a given value. It has recently been criticized (Allouche *et al.* 2006). The best that can be done with it is to refer, as the authors do, to a significance table given in Landis & Koch (1977).

Unfortunately, this table is a matter of opinion, as its originators admit, saying that it is '*clearly arbitrary*', and intended only as a '*benchmark*' for discussion of a specific example given by them. This specific example involved allocation of patients, by two neurologists, into four classes. In the words of a seminal author on the kappa coefficient (Cohen 1960) '*it is generally of little value to test κ for significance*'. In fact it is impossible (Allouche *et al.* 2006).

Miller *et al* (2007) also refer to Fielding & Bell (1997), who reviewed methods for assessing prediction errors by ecological models. In that review, a plethora (13) of untestable statistics is given. The thrust of the Fielding & Bell (1997) paper is, in their own words, '*to adopt a pragmatic approach to model building in which we concentrate on the model's accuracy and usefulness, rather than testing the statistical validity of the model*'. It is not clear why the authors considered this relevant to their methods.

In this paper, the null hypothesis of a real difference between fire dates derived from grasstrees, and those derived from satellite images, for the last three decades of the twentieth century, is tested. The first step in this was to cast the data into a set of contingency tables, using the corrected data, as shown in Table 1. Although the χ-squared statistic (Pearson 1904; Fisher 1944) is often used to test such tables for dissociation between the two classificatory variables, it has been suggested that, where there is spatial autocorrelation, the probability of a Type 1 error may be underestimated (Legendre 1993).

In the Eneabba data, there is possible spatial autocorrelation, in that grasstrees are contagiously flammable. Five grasstrees, within a few metres of each other, were examined at each site. If one burned, then there was a likelihood that one or more of the others would also burn. To overcome this potential source of error, the data for each decade were split into five separate contingency tables, each containing only one grasstree from each site.

In the analysis of fire ecology, presence and absence of fire are equally important, and so deserve equal attention in methodology. Given the several years usually needed for enough fuel to accumulate, and the often haphazard nature of ignition, the occurrence of fire will nearly always be rarer than its absence, but this is no reason to regard fire presence as more ecologically, or statistically, important than fire absence. In this paper, agreement on fire presence and fire absence are given equal methodological status, whilst recognizing that the latter is usually more common than the former.

There is an inherent cumulative error in the grasstree dating method as one moves down the stem. Due to the rain solubility of the growth rings, growth rates can usually only be estimated near the top, and are then extrapolated back in time. Previous work (Lamont & Downes 1979) suggests that grasstrees grow at a constant rate throughout their life, but even a few millimetres error in estimated annual growth rate can lead to a much larger error lower down the stem, that is to say, further back in the past. This cumulative error definitely applies to the estimated calendar years of fires. It varies in its effect on fire interval estimates. For longer fire intervals, say several decades, it can be significant. As fire interval estimates get shorter, the cumulative error between fires diminishes. When fire intervals are only a few years, the error is abolished, due to rounding to the nearest whole year.

Table 1

Contingency tables showing the data, corrected for errors and omissions in Miller *et al.* (2007). The method for determining agreement between grasstrees and satellite imagery is as explained in this paper. As in Miller *et al.* (2007), (a) is the entire study period 1973–2002; (b) 1993–2002; (c) 1983–1992; and d) 1973–1982.

		Satellite Record		
		+	–	Sum
(a) Grasstree record	+	97	115	212
	–	103	2535	2638
	Sum	200	2650	2850
(b) Grasstree record	+	58	11	69
	–	42	839	881
	Sum	100	850	950
(c) Grasstree record	+	22	45	67
	–	33	850	883
	Sum	55	895	950
(d) Grasstree record	+	17	59	76
	–	28	846	874
	Sum	45	905	950

In their paper, Miller *et al* (2007) briefly mention fire intervals, but concentrate on fire dates. Yet one of their criticisms is that the fire intervals estimated from grasstrees are too short for the survival of some plants. In contrast, this paper examines fire intervals in some detail, comparing those shown by the grasstrees, with those shown by the satellite images.

In Beekeepers' Reserve, while cleaning charcoal off grasstree stems to reveal fires over the past three decades, I also opportunistically recorded fire marks back to the 1920s on some older grasstrees. These data were given to the authors at the time, but were not used in their analysis. To set the three decades of data examined by the authors in temporal context, this present paper compares them with fire intervals derived from these older fire marks.

Results

The contingency tables ('confusion matrices') presented by the authors as their Table 2, and based on the data in their Figure 2, have errors. Miller *et al* (2007) say that the analysis includes 20 sites, each with 5

Table 2

Contingency tables for the data split into five subsets, to avoid spatial autocorrelation within sites. Only one of the five grasstrees at each of the 19 sites (sites 8 and 18 omitted) is used in each table. The conventional labeling for cells is used, that is the top row as a and b, the second row as c and d. The expected count under the null hypothesis of random distribution is given in brackets, rounded to an integer. In a few cases, where it is close to the observed value, a decimal place is included.

		a	b	c	d	Σ
Grasstrees (1, 6, 11 …)	1973–82	2 (1)	16 (17)	7 (8)	165 (164)	190
	1983–92	7 (1)	7 (13)	3 (9)	173 (167)	190
	1993–02	11 (1)	2 (12)	9 (19)	168 (158)	190
Grasstrees (2, 7, 12 …)	1973–82	2 (1)	10 (11)	7 (8)	171 (170)	190
	1983–92	6 (1)	9 (14)	5 (10)	170 (165)	190
	1993–02	12 (2)	3 (13)	8 (18)	167 (157)	190
Grasstrees (3, 9, 13 …)						
	1973–82	4 (1)	9 (12)	4 (7)	173 (170)	190
	1983–92	5 (1)	11 (16)	5 (9)	169 (165)	190
	1993–02	11 (1)	3 (13)	9 (19)	167 (157)	190
Grasstrees (4, 10, 14 …)	1973–82	5 (1)	13 (17)	4 (8)	168 (164)	190
	1983–92	5 (1)	10 (14)	6 (10)	179 (175)	190
	1993–02	13 (1)	1 (13)	7 (19)	169 (157)	190
Grasstrees (5, 11, 15 …)	1973–82	4 (1)	11 (14)	5 (8)	170 (167)	190
	1983–92	1 (.8)	12 (12.2)	10 (10.2)	167 (166.8)	190
	1993–02	11 (1)	2 (12)	8 (18)	169 (159)	190

Table 3

The data of Table 2 converted to signs. Plus (+) where the observed count exceeds the expected, and minus (–) where it does not.

		a	b	c	d
Grasstrees (1, 6, 11...)	1973–82	+	–	–	+
	1983–92	+	–	–	+
	1993–02	+	–	–	+
Grasstrees (2, 7, 12 ...)	1973–82	+	–	–	+
	1983–92	+	–	–	+
	1993–02	+	–	–	+
Grasstrees (3, 9, 13 ...)	1973–82	+	–	–	+
	1983–92	+	–	–	+
	1993–02	+	–	–	+
Grasstrees (4, 10, 14 ...)	1973–82	+	–	–	+
	1983–92	+	–	–	+
	1993–02	+	–	–	+
Grasstrees (5, 11, 15 ...)	1973–82	+	–	–	+
	1983–92	+	–	–	+
	1993–02	+	–	–	+

In a contingency table, comparing observed with expected fire occurrence and absence, the probability of a perfect match is small. In a 2 X 2 table, where there is not a perfect match between observed and expected counts, adjacent cells must have opposite signs, and diagonal cells the same sign. Therefore the probability of the pattern (+ – – +) is less than 0.5, so the probability of that pattern occurring 15 times in succession is less than $(0.5)^{15}$, or approximately .00003. We may reject the hypothesis of random allocation to cells, and conclude there is a significant pattern of agreement between grasstree and satellite fire dates, by both mutual presence of fire, and mutual absence.

grasstrees, over a period of 30 years, so giving a grand total of 3000 observations, or 1000 for each decade. Grasstree cleaning took place at 21 sites, but in their Figure 2 only 19 sites are shown, sites 8 & 18 being omitted. The authors only mention the omission of one unspecified site, due to satellite uncertainty. If we take the authors' Figure 2 as a basis, with only 19 sites included, then the correct grand total of observations for the data in Table 2 is only 2850, and only 950 for each decade.

There are other errors, for example the omission of eight grasstree records in Sites 19, 20 & 21, in which grasstrees and satellite agree, on the field sheets, that there was a fire. A further four fires which appeared on grasstrees within a calendar year of the satellite estimate (Sites 10 & 21) were also omitted by the authors.

With the authors' errors and omissions corrected, and the more reasonable definition of 'agreement' applied, my Table 1 gives the revised contingency tables. Table 2 shows the data split into five separate contingency tables, to avoid autocorrelation. Table 3, shows the data converted to signs (+ or –).

Although there is some agreement between fire dates derived from grasstrees and satellite photographs, it is not perfect. As noted by the authors, agreement is weaker as we move into the past. Where disagreement occurs, it may be due to errors in grasstree interpretation, or in satellite image interpretation, or in both. A pattern analysis of the numbers of fires identified by grasstrees and satellite imagery is given in Table 4.

Table 4

Pattern of the number of fires. Plus (+) means the grasstrees showed more fires than the satellite images; minus (–) means grasstrees showed fewer fires than satellite images. There were no cases of equal numbers.

	1973–82	1983–92	1993–02
Grasstrees (1, 6, 11...)	+	+	–
Grasstrees (2, 7, 12 ...)	+	+	–
Grasstrees (3, 9, 13 ...)	+	+	–
Grasstrees (4, 10, 14 ...)	+	+	–
Grasstrees (5, 11, 15 ...)	+	+	–

Assuming a small probability that grasstrees and satellites may identify exactly the same number of fires, the probability of the pattern (+ + –) occurring by chance is less than $(0.5)^3$. The probability of it occurring five times in succession by chance is less than $(0.5)^{15}$, or approximately .00003. We may reject the null hypothesis of chance occurrence, and conclude there is a real tendency for grasstrees to show more fires than the satellite images in the two earlier decades, and fewer in the last decade.

Table 5

Statistical summary of fire intervals shown by grasstrees and satellite images for the years 1973–2002. All 21 sites are included. We cannot reject the null hypothesis that the samples drawn by the two methods are from the same population ($p>.05$ by Mood's Median Test, and $p>.9$ for a t-test on the means).

Statistic	Grasstrees	Satellite Images
Mean	9.93	9.88
Standard Deviation	4.95	4.91
Standard Error or Mean	0.34	0.44
Skewness	0.85	0.58
Median	9	8
Minimum	3	2
Maximum	29	22
95% CI for Mean	9.27–10.59	9.01–10.75
95% CI for Median	8–10	8–9
N	218	125

As in Miller *et al.* (2007), all the above analyses concentrate on the calendar dates of the fires. Yet even if two successive dates from a grasstree stem are incorrect, the interval between them may be correct, although wrongly dated. As discussed above, for ecological understanding, the intervals between fires are more important than the exact date. I have, therefore, calculated the intervals between fires, for both grasstree and satellite methods, over the thirty years of the study. Key descriptive statistics are given in Table 5. Mood's Median Test and the t-test for means do not support rejection of the hypothesis that the means and medians are equal.

To give a longer term perspective, Table 6 compares the median fire intervals calculated from the grasstree data, including the data collected opportunistically, back to the 1920s, with the median fire intervals calculated from the authors' satellite interpretation over the three recent decades.

Figure 1 shows the interval data, for grasstrees back to the 1920s, and for satellite interpretation back to 1973.

Table 6

Descriptive statistics, by decade, for fire intervals from grasstrees and satellite data. Opportunistically collected grasstree data back to the 1920s are included. For the satellite data, there were no previous records from which to estimate fire intervals before the 1980s.

	Intervals from satellites				Intervals from grasstrees			
Decades	Min.	Median	Max.	N.	Min.	Median	Max.	N.
2000s	2	7	18	45	3	13.5	29	44
1990s	9	14	22	50	4	10	17	50
1980s "	6	8	8	30	3	8	21	85
1970s					3	6	16	67
1960s					2	5	21	66
1950s					1	4	18	54
1940s					2	3	10	33
1930s					2	2	9	18
1920s					2	4	6	3

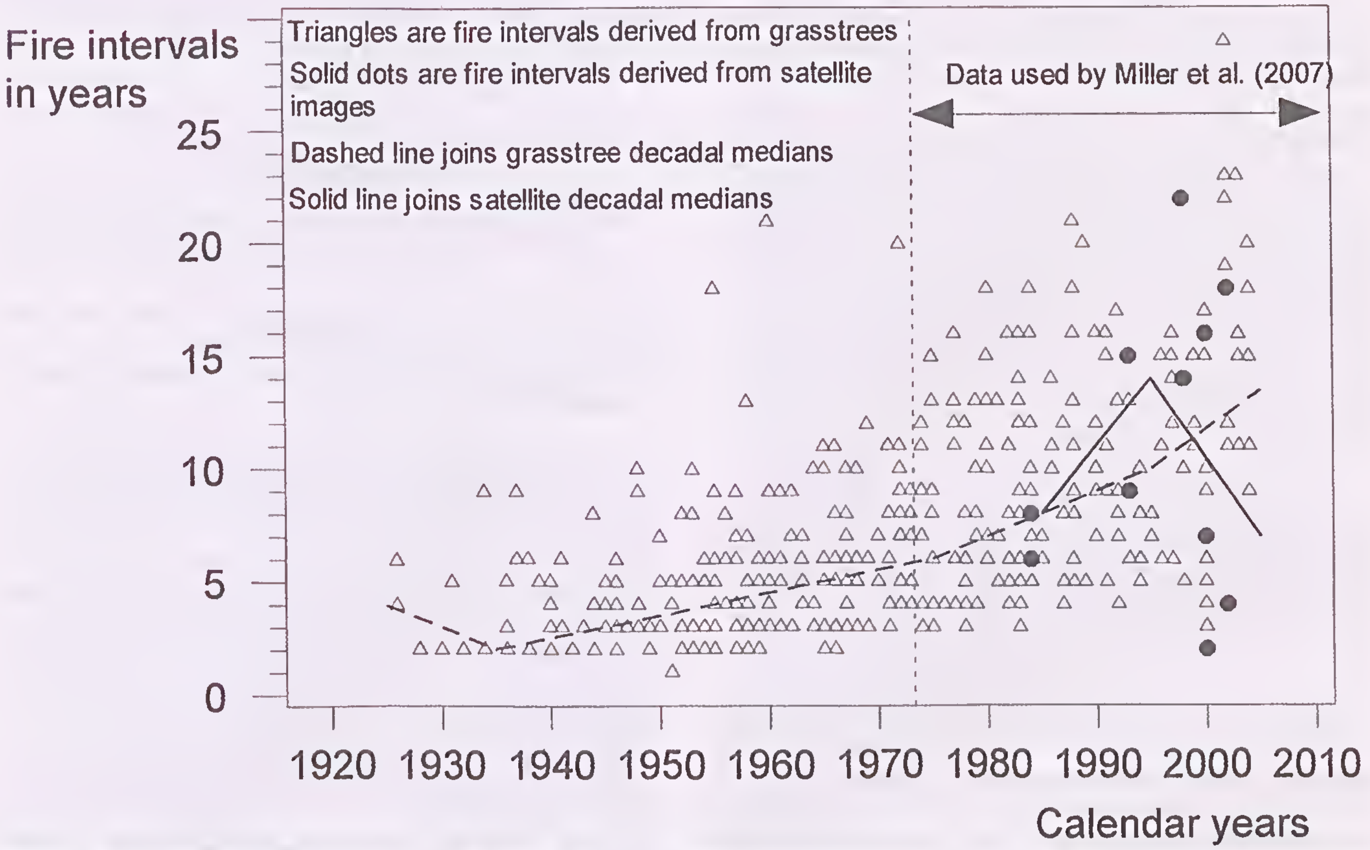

Figure 1. Interval data, for grasstrees back to the 1920s, and for satellite interpretation back to 1973. The median intervals from Tale 6 are included.

The median intervals from Table 6 are included. The grasstree data show a steadily lengthening of fire interval over the last century, which agrees with extensive previous grasstree data collected from more southerly vegetation, such as the *jarrah*, *tuart*, and *wandoo* forests (Ward 1996; Ward & Van Didden 1998; Ward *et al.* 1998, Ward 2001). The satellite fire intervals fall within the range of the grasstree fire intervals, and show a non-monotonic sequence of shorter, longer, then shorter median fire intervals in the *kwongan*.

Discussion

The grasstree cleaning at Eneabba was done in November 2004. In the following month, a very intense bushfire, much of it in long-unburnt fuel, burnt most of the Beekeepers' Reserve (Plozza & Groenhide 2005). Using the authors' method of satellite interpretation, this would have been incorrectly dated as a 2005 fire. Assuming, as the authors do, that fire dates derived from satellite photographs are 'true', grasstrees correctly showing the fire in 2004 would have been counted, by the authors, as 'false positives'. Similarly, grasstrees not showing the fire in 2005 would have been counted as 'false negatives'.

Local information is that such large summer fires were unknown in the past. According to a local farmer and fire fighter (Gillam 2005), up to the 1950s the *kwongan* heath in Beekeepers' Reserve was burnt as a mosaic of strips and patches, in winter or early spring, by mounted

Aboriginal kangaroo shooters, whose names are remembered. The shooters, now deceased, burnt to bring up winter grass, and so attract kangaroos. The winter grass was probably largely the native annual *Austrostipa compressa*, which still germinates profusely after fire in *kwongan*.

Remembering the importance of consilience, there are *djiridji* (*Macrozamia riedlii*) in the *kwongan*. Since *djiridji* are prolific nitrogen fixers for 3–4 years after fire (Grove *et al.* 1980), regular burning would have had an important benefit for them, and probably other *kwongan* plants. Under long fire exclusion this nitrogen fixation would be largely lost, and that loss exacerbated by occasional fierce summer fires, like that of December 2004, which must lose vast amounts of nitrogen over large areas, through gasification, volatilization, and ash convection (Wan *et al.* 2001).

I noted on the field sheets, and the authors comment on, the occurrence of fire marks under seemingly unburnt thatch. The authors suggest this supports their doubts about the grasstree method. Practical understanding of bushfire, and ways of fighting it, suggest otherwise. Firefighters will sometimes light grasstrees deliberately, to remove fuel from the path of an advancing bushfire. When they do so, they often dampen the thatch with short bursts from a hose, to keep the fire relatively mild. If, perhaps due to a wind shift, the main fire does not reach those grasstrees, there may be only part combustion of thatch, but a fire mark on the grasstree stem may nevertheless occur. Lighting grasstree thatch which is wet from rain, or even dew, can have a similar partial burning effect.

It is a common observation that, even when grasstrees do not burn, smoke drifting from a nearby fire can provoke flowering. The influence of smoke on grasstree flowering has been noted more formally (Gill & Ingwerson 1976). In the very poor sand of the *kwongan*, the effort of such flowering might, due to lack of nutrient, cause the sudden death of some green needles, so preventing the withdrawal of anthoquinone, and creating a black mark on the stem. Such sudden needle deaths would likely be more prevalent where there was no nutrient from ash, and where nearby legumes or *djiridji* had not been stimulated, by burning, into fixing nitrogen. As suggested by the authors, apparent fire marks on grasstrees which have not actually burnt, but have possibly been affected by smoke, are worth further investigation.

Without further satellite image interpretation, the authors have extrapolated their criticisms of the grasstree work to the *jarrah* forest, where there has long been a debate over the use of deliberate burning at relatively short intervals.

Jarrah is noted for its remarkable resistance to fire, even within a few years of germination, and forest experts have stated that it was, up to the 1920s, burnt every 2–3 years (Harris 1882; Hutchins 1916), or every 3–4 years (Hutchins 1916; Lane-Poole 1921; Stoate & Helms 1938), or every 2–4 years (Wallace 1966).

Stoate & Helms (1938) wrote that '*Jarrah as a species is remarkably resistant to fire*', and, referring to times before 1920, that '*it was unusual for any area of jarrah forest to escape periodic burning by at least a light ground fire for more than 3–4 years…*'. Hutchins (1916), who disliked forest fire, wrote that '*The jarrah forest, like most of the eucalypt forests, is liable to be burnt every two to three years…*'.

We should not ignore the well known rabbit plague of the 1920s and 1930s as a potential historical factor in changing *kwongan* fire frequency and intensity (Luke & McArthur 1977). More grass and forbs would support more frequent, mild, patchy fires, especially in winter or spring. Less fine fuel, and more woody fuel, would support more intense, less patchy fires, less frequently.

Miller *et al* (2007) say that fires in *kwongan* at 3–4 year intervals are incompatible with '*the absence of continuous fuels for carrying fire in shrublands*'. Yet, in their own Figure 2, their interpretation of satellite images shows fires in recent decades, at several sites, at 2 and 4 year intervals. It is important, in discussion of *kwongan* fuels, to distinguish between ground litter, and elevated shrubs. Driven by wind, a fire in heath can spread through the shrubs, even if there is sparse and discontinuous litter on the ground.

Conclusions

In *kwongan* heath, near Eneabba, Western Australia, a comparison between fire history reconstructed from grasstree stems, and that reconstructed from satellite images, shows overall agreement on fire dates, and close agreement on fire intervals, over the last three decades of the twentieth century. While agreement is not perfect, it is unlikely to occur by chance.

From the evidence available, it is not possible to say whether disagreements on fire dates are due to errors in satellite interpretation, or in grasstree interpretation, or in both. Of more ecological interest is the very close agreement between the mean fire intervals shown by the two methods, which supports the general validity of fire intervals derived from older grasstrees, extending back to the 1920s at Eneabba, and back to the 1850s elsewhere in the *kwongan*, at Yardanogo Reserve (Enright *et al.* 2005). These show regular burning at 2–5 year intervals.

There are, doubtless, errors in the grasstree data, as expected when measuring rough, contorted objects in the field. The grasstrees cleaned at Eneabba were notably smaller, and more contorted, than those cleaned further south (*e.g.* Ward & Van Didden 1998). To expect laboratory precision is unrealistic. At the same time, the grasstree technique can identify past small fires, including deliberate burning of individual grasstrees, or small groups thereof, by humans. Satellite images seem, as yet, to have insufficient resolution to detect such small scale burning.

In view of the history of human activities in Beekeepers' Reserve, past small scale burning is a likely reason for some of the disagreement between satellite and grasstree data. Using the authors' terminology, the satellite images are prone to 'false negatives', failing to identify small fires; and 'false positives', by failing to identify, within a burnt area, some grasstrees, or small patches, that have remained unburnt. Small scale burning in the past is also a likely cause of some disagreement between fire dates on individual grasstrees.

Bushfire ecology, behaviour, and history are very important aspects of West Australian ecology. They are inextricably entwined. The past fire intervals shown by grasstrees have potentially deep ecological significance in understanding changes in fire frequency, behaviour, and mosaic pattern since European arrival in Australia. More grasstree research is needed, and, for consilience, more research into historical information held in the local community.

On present evidence, frequent burning of a mosaic of interlocking strips and patches, in winter and early spring, is the most likely way to protect the *kwongan* from uncontrollable summer fires, burning on a broad front. We have much to learn about the significance of season, time of day, shade, humidity, soil moisture, slope, lighting pattern, wind speed, and wind changes, in using deliberate heath fires as a management tool, for both human safety and nature conservation. Aboriginal Elders may be able to help (Bird *et al.* 2008).

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A case for *in situ* management of Western Ringtail Possums, *Pseudocheirus occidentalis,* in development areas

S A Thompson[1] & G G Thompson[2]

[1] Coffey Environments
PO Box 4223 Victoria Park, WA 6979, Australia
✉ scott_thompson@coffey.com

[2] Centre for Ecosystem Management
Edith Cowan University, Joondalup, WA 6027, Australia
✉ g.thompson@ecu.edu.au

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Abstract

The threatened Western Ringtail Possum (*Pseudocheirus occidentalis*) is relatively abundant in numerous locations on the coastal strip between Bunbury and Dunsborough, Western Australia. But this area is subject to rapid residential development and there is the inevitable conflict between protecting a threatened species and development. We recorded 306 dreys, mostly in Peppermint trees, in the Dunsborough town site. Areas with high concentrations of dreys did not necessarily coincide with where most possums were found foraging. Over six nights 118 *P. occidentalis* were seen in road side verges, 246 in remnant vegetation and 53 in residential areas, indicating that they are abundant in this highly disturbed habitat. We use these data to discuss potential management options (*i.e.*, no development, do nothing, translocate or *in-situ* management) for new development sites in the region.

Keywords: Western Ringtail Possum; *Pseudocheirus occidentalis,* threatened species, management, translocations, Western Australia

Introduction

Pseudocheirus occidentalis is listed as a Schedule 1 species (*i.e.*, fauna that is rare or likely to become extinct) under the Western Australian Wildlife Conservation (Specially Protected Fauna) Notice 2008, and as Vulnerable under the Commonwealth *Environment Protection and Biodiversity Conservation* (EPBC) Act 1999. It is also listed as Vulnerable in the IUCN Red List of Threatened Species (http://www.iucnredlist.org/details/18492).

Under the EPBC Act any action that is likely to have a significant impact on a matter of national environmental significance requires assessment and approval by the Commonwealth Minister for the Environment before that action can proceed. General guidelines for what the commonwealth considers a significant impact on a species are available in a Department of the Environment and Heritage (2006) publication. In 2009, the Commonwealth Department of Environment, Water, Heritage and the Arts (2009a) released its policy guideline indicating what it considered as significant impact thresholds and actions that might impact on *P. occidentalis.*

As a consequence of legislative requirements and the Commonwealth government's signalled intent, most land developers along the coastal strip between Bunbury and Dunsborough in Western Australia are required to undertake a field survey to determine the presence of *P. occidentalis* in order to assess the potential impact of the proposed development on this possum.

Jones *et al.* (1994a), de Tores (2008) and the Department of Environment, Water Resources and Heritage (2009b) indicated that *P. occidentalis* is now most found along the coastal strip of vegetation between Bunbury and Dunsborough, but scattered populations are also present throughout the south-west as far east as Albany (Jones *et al.* 2007). *Pseudocheirus occidentalis* is nocturnal and usually shelters by day in a drey (bird-like nest) or tree hollow. Dreys are typically located in the crown of Peppermint trees, but may be constructed in other tree species, such as Melaleuca, Banksia, Marri, Tuart and Jarrah trees. Where the vegetation is not suitable to make a drey, tree hollows are utilised as retreats (Jones *et al.* 1994a). In this general area *P. occidentalis* will also make use of dense ground cover (*e.g.*, sword grass) for daytime refuge and also grass trees, reeds, sedges, blackberry thickets, fallen logs and disused rabbit warrens (Harewood 2008; de Tores 2008). *Pseudocheirus occidentalis* are territorial and have defined, overlapping home ranges of 0.5–1.5ha that extend about 60m from their drey tree (Jones *et al.* 1994b). An individual may have numerous dreys within its home range. In the coastal region, the leaves of Peppermint trees are a primary food source (Jones *et al.* 1994b), but individuals in residential areas may also feed on a variety of other tree foliage as well as domestic garden plants, fruit and vegetables. In Eucalypt dominated woodlands, with fewer Peppermint trees other vegetation will be eaten (Jones *et al.* 1994b, de Tores 2008).

The specific objective of this paper is to briefly describe the locations of *P. occidentalis* and their dreys within a section of the Dunsborough town site and to discuss potential management options that arise from these data for developments in the south-west of Western Australia.

Methods

Survey Site

A section of the Dunsborough town site (Figures 1 and 2) was surveyed by four people between 25 and 31 March 2007. The surveyed area was divided into three zones; remnant vegetation (47.8ha); residential (57.4ha); and road side verges (21.7ha). The purpose of the survey was to record the location of all dreys within the area and to count the number of *P. occidentalis*. Both day and night searches were undertaken to accomplish this task.

Day-time Searches

Dreys were located during the day by systematically searching the area on foot. All dreys were numbered and their location recorded using a hand-held GPS. Although we could find no data to suggest drey type was connected to usage or abundance, there is a variation in the construction of dreys that we consider may provide an index of use with further investigation (Lindenmayer *et al.* 2008). Therefore, dreys were classified into one of four categories:

Type 1 dense, well-made ball or slightly elongate form with a distinct entrance hole. In this type of drey the possum is completely enclosed;

Type 2 dense, well-made cup-shaped nest with some material over the top, but the possum is not fully enclosed;

Type 3 dense, well-made cup-shaped nest with an open top. The possum sits deep inside the cup of the drey and may not be visible from the ground;

Type 4 platform of twigs, often in a tree or branch fork, with no more than a shallow depression where the possum rests.

For each drey the following information was recorded: drey category, tree species, height of the tree (estimated), height of the drey above the ground (estimated), condition of the drey and the presence of a possum(s). Dreys were easily detected and therefore a near complete list can be provided for each of the tree habitat types.

Night-time Searches

Night searches were used to locate *P. occidentalis*. This was done by searching for individuals using a head torch while walking through the area between 1930 and 0200hrs. Due to the size of the survey area it was not possible to cover all of the area every night. No area was searched on multiple occasions on a single night, but each area was searched on at least two occasions on non-consecutive evenings. A different combination of observers searched each area during the second search of the area.

Weather

Skies were clear and suitable for spotlighting on five of the six evenings. On 27 March it rained and was windy. Although *P. occidentalis* were still observed, the evening search was stopped at 2300hrs when the weather deteriorated to avoid inconsistent observations due to inclement weather. Possums were observed to be retreating to sheltered areas (*e.g.*, tree hollows) and had stopped feeding when the rain began to get heavy.

Limitations

We acknowledge that there were likely to be observer differences in detecting *P. occidentalis* using spotlights (Wayne *et al.* 2005), but this was not crucial to this study as no attempt was made to estimate densities or relative abundance, rather it was to indicate which habitat types were being utilised.

In addition, it was unlikely that all *P. occidentalis* were observed each evening in the areas searched, as possums will often turn their head or close their eyes when a light is shone nearby. These behavioural responses make spotlighting counts difficult given that eye-shine is the primary method for locating individuals in the tree canopy. Possums that inhabited residential dwellings and backyards that could not be accessed were not counted. The drey and possum counts for residential areas are therefore almost certainly an under-estimate.

Differences among estimates of drey height were not statistically examined as there was likely to be 'measurement' error in the estimates, limiting any quantitative analysis.

Results

Dreys

A total of 306 *P. occidentalis* dreys were recorded in the study area (Figure 1). The height and rating of each drey is summarised in Table 1. The average height of a drey above the ground level was 5.3m with a range of 1.5–25m. Dreys located in the residential area had the highest mean height (5.8m), while the dreys located in the roadside vegetation had the lowest mean drey height of 4.8m. The majority of dreys were either type 1 or 2 (69%),

Table 1

Height, rating and density of dreys

Location	Drey abundance	Drey height (m)		Drey rating				Drey density/ha
		Mean ± 1 se	Range	1	2	3	4	
Roadside verges	54	4.8 (0.341)	1.8–12	22	16	9	7	4.56
Remnant vegetation	153	5.2 (0.237)	1.5–25	52	50	33	18	1.13
Developed areas	99	5.8 (0.276)	1.5–15	38	34	15	12	2.66
TOTAL	306	5.3	1.5–25	112	100	57	37	2.41

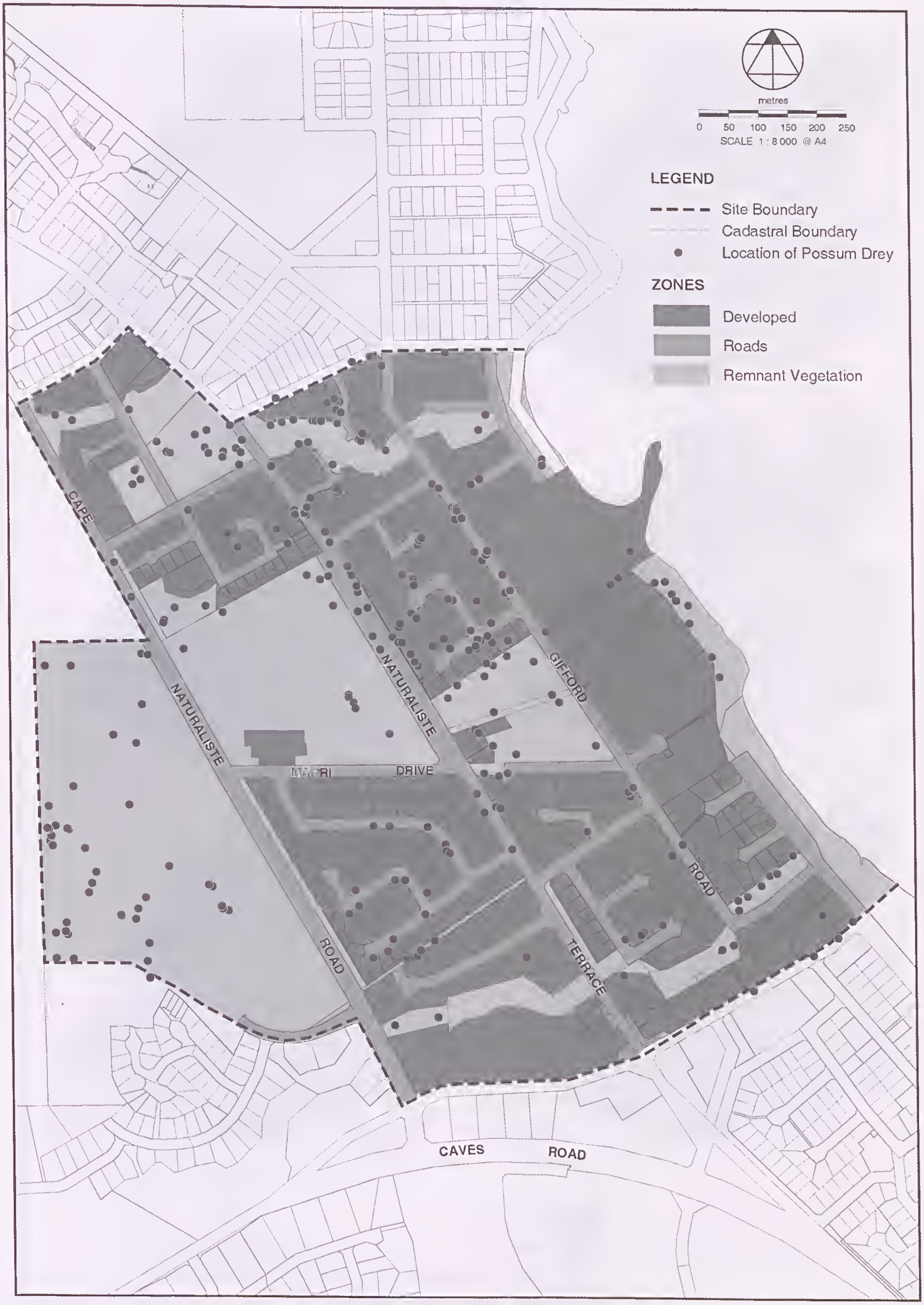

Figure 1. Locations of *Pseudocheirus occidentalis* dreys in the Dunsborough town site.

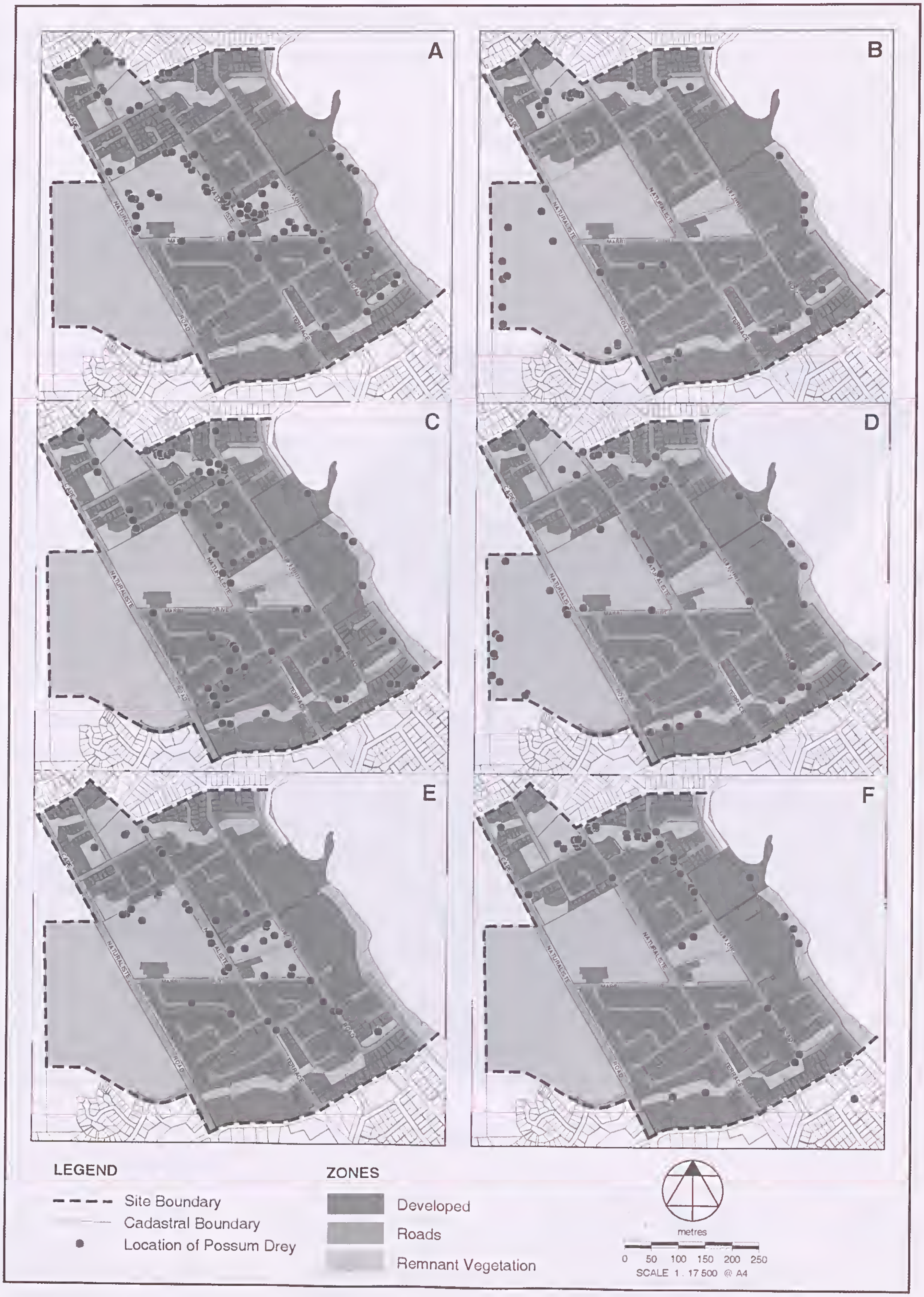

Figure 2. Locations of *Pseudocheirus occidentalis* in the Dunsborough town site on the six search occasions.

followed by type 3 and then type 4. The density of dreys was lowest in the remnant vegetation (1.13/ha) and highest in roadside vegetation (4.56/ha). The density of dreys across the survey area was 2.4/ha (Table 1). Dreys were recorded in a variety of trees, but most were in Peppermint trees (43.9%) with the next most common locations being Melaleuca, Banksia and Marri trees (19.6%, 12.7% and 12.4% respectively; Table 2).

Pseudocheirus occidentalis

One hundred and nine *P. occidentalis* were observed on 25 March; 55 on 26 March; 91 on 27 March; 63 on 28 March; 51 on 29 March; and 52 on 30 March. Overall 246 observations were made in remnant bushland, 118 in roadside verges and 53 in residential areas (Table 3). The majority of *P. occidentalis* were recorded in Peppermint trees (60%) followed by Marri trees (16%). In the

Table 2

Numbers of *P. occidentalis* dreys detected in different tree types in each of the sampled habitats in the Dunsborough town site.

Tree type	Roadside verges	Remnant vegetation	Developed areas	TOTAL	% of Total
Peppermint	31	46	57	134	43.8
Melaleuca	10	43	7	60	19.6
Banksia		38	1	39	12.7
Marri	7	13	18	38	12.4
Eucalypt	2	1	2	5	1.6
Acacia	1		3	4	1.3
Bamboo/Pine			4	4	1.3
Allocasuarina		3		3	1.0
Bottlebrush	1		2	3	1.0
Jarrah		2		2	0.7
Kunzea		2		2	0.7
Pine			2	2	0.7
Planted/introduced	1		1	2	0.7
Bamboo		1		1	0.3
Chinese Pepper		1		1	0.3
Hakea	1			1	0.3
Hakea/Wisteria		1		1	0.3
Hibiscus			1	1	0.3
Pitossporum		1		1	0.3
Woody Pear		1		1	0.3
Yate			1	1	0.3
TOTAL	54	153	99	306	

Table 3

Pseudocheirus occidentalis locations and use of tree species

Tree type	Roadside verges	Remnant vegetation	Residential	TOTAL	% of Total
Peppermint	59	159	32	250	59.95
Marri	29	35	3	67	16.07
Banksia	2	20		23	5.52
Melaleuca	8	5	4	17	4.08
Acacia	2	8	1	11	2.64
Eucalypt	4	5	2	11	2.64
Fence	2	2	6	10	2.40
On the ground	1	3	1	5	1.20
Tuart		4		4	0.96
Allocasuarina	2	1		3	0.72
Bottlebrush	2		1	3	0.72
Jarrah		2		2	0.48
Lilly Pilly			2	2	0.48
On the roof	3			3	0.72
Hakea/Wisteria		1		1	0.24
Lemon tree	1			1	0.24
Moptop	1			1	0.24
Planted/introduced tree		1	1	2	0.48
Woody Pear	1			1	0.24
Other				4	
TOTAL	118	246	53	417	

residential areas, *P. occidentalis* were observed utilising roofs, fences and a variety of exotic shrubs and trees in addition to native vegetation.

Discussion

It is apparent that *P. occidentalis* utilised residential areas, remnant vegetation and trees in roadside verges. Dreys were located in all habitat types; however, they were least abundant in the remnant vegetation. As possums will readily retreat to tree hollows, the lack of dreys in remnant vegetation might simply reflect a higher number of available tree hollows.

Jones *et al.* (1994b) recorded densities of *P. occidentalis* between 2.5 and 4.5 per hectare at the Abba River and the Locke Estate, Busselton, although elsewhere (*e.g.*, Geographe Bay and Emu Point) densities were less than 1.0 per hectare. Harewood (2008) reported average densities of *P. occidentalis* of 13.5 per hectare within urban reserves in Busselton. Jones *et al.* (2007) reported 30 *P. occidentalis* in 85 hectares of pastoral land, 170 in 50 hectares of a C class nature reserve, 200 in 35 hectares of beachside settlements and 270 in 35 hectares of beachside recreation reserve (A class) used for camping since 1955 in the Siesta-Kealy area south of Busselton. So although the species is listed as threatened under state and commonwealth legislation, it was relatively abundant in the highly disturbed Dunsborough town site and in reserves within the town of Busselton and was in much higher densities in the beachside Peppermint woodland south of Busselton.

Dreys ranged in height above the ground from 1.5–25m, with the developed areas having the highest and roadside verges having the lowest. This largely reflects the availability of trees in these areas, as the Pines, Chinese Peppers, etc in residential properties were generally taller than street trees which are mostly Peppermints.

The majority of *P. occidentalis* dreys recorded within the study area and in each of the habitat types were types 1 or 2. *Pseudocheirus occidentalis* were most often found in Peppermint trees, but as no assessment was made of the availability of tree types, this may reflect the abundance of these trees in the area rather than any selective preference. It is however, apparent that *P. occidentalis* forage and retreat to a variety of tree types, and will also utilise artificial structures (*e.g.*, compost heaps, houses, poles, power lines). Maps produced by Jones *et al.* (1994b) suggested the locations of dreys and possums were similar at their study site. However, possums foraging (Figure 1) at night in Dunsborough did not cluster in areas of higher drey density (Figure 2), which suggests that possums utilised a variety of trees in their home ranges in which to forage.

These data suggest that the Dunsborough town site is an important area for maintaining the population of *P. occidentalis* in the south-west of Western Australia. The Department of the Environment, Water, Heritage and the Arts (2009a) Policy Statement 3.10 on *P. occidentalis* does not include the Dunsborough town site as a 'core habitat' area, which is surprising given the number of possums in the town. We have also recorded *P. occidentalis* in other areas south of Dunsborough, which suggests there is a need for a more detailed and comprehensive assessment of their geographic distribution in the south-west of Western Australia. Without a detailed knowledge of their current geographic distribution in the area, it is difficult to assess the potential impacts of proposed developments in town sites on this species in the general area. The recent reports by Harewood (2008) and Jones *et al.* (2007) for the GeoCatch Council provide evidence of how little we know of the current spatial distribution and their relative abundance.

Management implications

If *P. occidentalis* are present in a proposed development area, then there are potentially four management options: a) stop the development from proceeding, b) do nothing and ignore the presence of *P. occidentalis*, c) capture and translocate individuals to another suitable location, and d) manage the population *in situ*.

Stopping a development is an option that is likely to provide the highest level of protection. However, elsewhere in Western Australia the presence of rare and endangered species in a development area has usually not been sufficient to stop the development (*e.g.*, Barrow Island development potential impact on flatback turtles; EPA Bulletin 1221, 2006), so this may be an unrealistic option.

As developers can be prosecuted under the EPBC Act (1999) if a development significantly impacts on *P. occidentalis*, it is advisable to make a referral to the Commonwealth Environment Minister under the EPBC Act (1999) if they are on a development site. The Commonwealth Department of Environment, Water, Heritage and the Arts (2009) released a policy guideline for addressing the issue. This policy paper only addresses *P. occidentalis* within the coastal zone (~15km from the sea) between Bunbury and Dunsborough. This area has been divided into core habitat (*i.e.*, high densities of *P. occidentalis*), supporting habitat (*i.e.*, buffer zone and areas offering foraging, breeding and dispersal opportunities) and primary corridors (connections between core habitats). Thus, the option of doing nothing and ignoring the presence of *P. occidentalis* is not available to a developer in this area. Few recommendations are offered on managing *P. occidentalis* in development areas in the policy statement.

Capturing and translocating *P. occidentalis* has been attempted at numerous locations including into Leschenault Peninsula Conservation Park, Yalgorup National Park and Lane Poole Reserve (see review in de Tores *et al.* 2004, and also de Tores *et al.* 2005; 2008). The summary review by de Tores *et al.* (2004) suggested many individuals translocated into the Leschenault Peninsula Conservation Park died after translocation. Possible reasons for these deaths were competition from Brushtail Possums (*Trichosurus vulpecula*), predation by cats (*Felix catus*), foxes (*Vulpes vulpes*) or pythons (*Morelia spilota imbricata*), prey switching [rabbit (*Oryctolagus cuniculus*) numbers had been significantly reduced], effects of drought, disease and unsuitable habitat. The most likely reason was predation by foxes as the frequency of the 1080 baiting program had become erratic (de Tores *et al.* 2004). Augee *et al.* (1996) reported that hand-reared *Pseudocheirus peregrinus* released into the Ku-ring-gai Chase National Park in New South Wales survived for an average of 101 days compared with wild ringtail possums and most died as a consequence of predation by foxes (52%) and cats (29%). Early data for translocations to Yalgorup National Park and Lane Poole Reserve suggested that small populations might have been established (de Tores *et al.* 2008), but long-term survival of these populations will only be known with future monitoring. de Tores *et al.* (2008) expressed the view that translocations have increasingly been used as a mitigation measure for many threatened species and suggested they have a major role to play in conserving *P. occidentalis*. The Commonwealth Government (Department of Environment, Water, Heritage and the Arts 2009b) background to the policy statement indicates that 'translocation does not reduce the impact of an action, and is not considered to be a mitigation or offset measure as it is unlikely to result in a positive conservation outcome for the species'. It is our view that the translocation of individuals into 'presumed suitable' habitat that is devoid of the species may doom translocated individuals to suffer the same fate as those in the Leschenault Peninsula Conservation Park. Understanding why *P. occidentalis* are not present in 'presumed suitable' habitat within their known geographic distribution is an important precursor to successful translocations, as it enables management strategies to be put in place to mitigate these threats. For example, if *P. occidentalis* have become locally extinct in an area due to fire or fox predation, then the management strategies would be entirely different to enhance the survival of translocated individuals.

Jones *et al.* (1994a) reported extant populations of *P. occidentalis* outside the urban area occurred in areas associated with water courses, drainage lines and swamps with habitat characterised by their near-coastal position and high continuity of canopy or mid-strata vegetation. More recently, Jones *et al.* (2007) have reported substantial populations in disturbed but non-urban areas between Busselton and Dunsborough and Harewood and our data demonstrate that *P. occidentalis* are also able to survive and maintain relatively high densities within urban areas. It therefore seems appropriate to maintain existing *P. occidentalis* populations *in situ* as the preferred management strategy in new development areas. Being arboreal, feeding in the tree canopy, being relatively slow and clumsy on the ground and preferring to move through the tree canopy rather than come to the ground provides a planning framework for ensuring their coexistence with human habitation (Jones *et al.* 1994a, b; pers. observation).

The tree canopy and connectivity of habitat are likely to be important for the survival of *P. occidentalis* whose home ranges have been affected by clearing. To reduce the number of individuals forced out of an area, developments should retain undisturbed habitat with an abundance of mature trees providing adequate foligae and hollows (Jones *et al.* 2007). Residential areas should be developed in stages over a number of years, retaining as many of the existing trees as possible and implementing a planting program of 'advanced' trees. A development restriction might, for example, only allow a proportion of the total development area to contain a prescribed density of immature trees. As trees grow and mature and thus become suitable habitat for *P. occidentalis*, new areas can be developed. Such an approval condition would provide an incentive for land developers to plant 'advanced' trees at a density that would sustain *P. occidentialis* in the new residential developments within a minimum timeframe.

Small residential blocks that are mostly covered with buildings offer limited space for growing large trees and obtaining the necessary connectivity among trees. Therefore, it might be important that these new residential developments have larger lots, controls on tree clearing, and are accompanied by active planting of trees on housing lots and roadside verges prior to the sale of the land. Developers might also be requried to construct physical linkages among trees (*e.g.*, wire cables, ropes) to provide improved connectivity. Local government can enhance *P. occidentalis* habitat by planting Peppermint trees sufficiently close together on the street verges and in public open space to provide connectivity corridors that enable possums to move between residential areas and public open space.

Given that cats could contribute to the decline in *P. occidentalis* (Augee *et al.* 1996; de Tores *et al.* 2008; Department of Environment, Water, Heritage and the Arts 2009b), caveats might also be placed on the land titles to either ban residents owning cats or compelling owners to keep their cats inside at night. Strategically locating public open space provisions to protect high quality *P. occidentalis* habitat and to offer strong connectivity among trees in roadside verges and residential properties might also be important.

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Two aquatic bioregions proposed for the South Coast Region, Western Australia

B A Stewart[1]

[1] Centre of Excellence in Natural Resource Management,
University of Western Australia, PO Box 5771 Albany WA 6332
✉ bcook@cyllene.uwa.edu.au

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Abstract

A need for the development of a bioregionalisation for Australian rivers using aquatic fauna has been recognised. This study was aimed at delineating and describing interim aquatic bioregions for the South Coast region in Western Australia. Macroinvertebrates were collected from 33 waterways located across the region, and data were analysed using cluster analysis. Two broad aquatic bioregions were identified, the Western South Coast bioregion, consisting of rivers lying from Gardner River in the west to the Bluff River, and the Eastern South Coast bioregion, consisting of the Pallinup River through to the Thomas River in the east. Rivers located in the latter bioregion were significantly more saline, slightly more alkaline, and had higher levels of total nitrogen than those located in the Western South Coast bioregion. Many species proved significant in distinguishing the two bioregions. The successful implementation of a biotic classification method to delineate aquatic bioregions for the South Coast Region indicates that the approach may be easily instituted and adapted for other regions within Western Australia, and could be undertaken using macroinvertebrate data generated by past sampling programs.

Keywords: Aquatic bioregions, aquatic fauna, macroinvertebrates, South Coast Region, Western Australia

Introduction

Bioregionalisation is a form of spatial classification which delineates areas of relatively homogeneous features that are distinct from other regions (Omernik 1987; Jenerette *et al.* 2002; Kingsford *et al.* 2005; Mackey *et al.* 2008). The recognition of such areas aids the assessment of rivers based on ecological values, as it allows the scoring of criteria such as 'naturalness', 'representativeness', 'rarity' and 'diversity' relative to a particular river type (Dunn 2000; Bennett *et al.* 2002). The Interim Biogeographic Regionalisation of Australia (IBRA) is a continent-wide regionalisation of landscape patterns, based on climate, geomorphology, landform, and terrestrial biota (Thackway & Cresswell 1995). However, this regionalisation has been shown to have significant limitations for describing the distribution of riverine biota (Turak *et al.* 1999; Marchant *et al.* 2000; Turak & Koop 2008), as has been the case for other landscape classifications (Hawkins *et al.* 2000; Hawkins & Vinson 2000; Heino & Mykra 2006). This has led to a recommendation for the development of a national classification for Australian rivers using aquatic taxa (Hart & Campbell 1994; Kingsford *et al.* 2005). However, such a national riverine classification has yet to be developed, although there have been some regional and State-wide river classification initiatives, with Victoria and New South Wales (NSW) receiving the most attention. Newall & Wells (2000) produced both a physicochemical regionalisation and a macroinvertebrate regionalisation for Victoria, while Turak *et al.* (1999) classified river sites in New South Wales using a predictive model approach, mapping their 'site groups', and Turak & Koop (2008) suggested that the large-scale spatial patterns they observed in their study provided some indication of what appropriate freshwater ecoregions of NSW may look like. In another recent study, Growns & West (2008) defined six aquatic bioregions within NSW based on the theoretical natural distributions of native fish species. The delineation of aquatic bioregions for the South Coast region in Western Australia has yet to be attempted, while the only riverine bioregionalisation existing for Western Australia is the scheme of proposed freshwater fish biogeographic provinces suggested by Unmack (2001).

The overall objective of this project was to delineate and describe interim 'aquatic bioregions' for the South Coast region. This region is one of six recognised for Western Australia, all of which were established by the Commonwealth Government of Australia to facilitate the integrated delivery of natural resource management across Australia. The South Coast covers more than 5.4 million hectares, and includes all southerly-flowing rivers from near Walpole in the west to beyond Cape Arid in the east. Of the approximately 107 rivers or major tributaries occurring in the region, the Frankland River (about 200,000 ML annual average flow) is the largest. Three IBRA bioregions (incorporating four 'sub-regions') occur in the South Coast Region: the Fitzgerald (ESP1) and Recherche (ESP2) sub-regions which together make up the Esperance Plains (ESP) bioregion, the Warren (WAR) bioregion and the Jarrah Forest (JF) bioregion (Thackway & Cresswell 1995).

A universally accepted methodology for the identification and mapping of biogeographical regions is still to be developed (Mackey *et al.* 2008). A classification of rivers could be based on either biological or biophysical (*e.g.*, geomorphic or hydrological) data, or a combination of these to define different bioregional types. Since previous testing of the Interim Biogeographic Regionalisation of Australia (IBRA) for representing aquatic ecosystems in Victoria found that this largely biophysical regionalisation was ineffective in characterizing macro-invertebrate assemblage distributions across that State (Marchant *et al.* 2000), an approach was adopted to delineate interim aquatic bioregions for the South Coast region based on macroinvertebrate community composition. Such an approach defined empirically-based bioregions for use in managing (and assessing ecological values) of aquatic ecosystems, rather than highlighting the causal factors behind the regionalisation. Geographical patterns were generated by agglomerating a number of spatial units (catchments) into groups based on a measure of biological similarity. This approach recognises that the resulting bioregions could be spatially disjunct, adjacent or nested, depending on the measured similarity (Mackey *et al.* 2008). Wells *et al.* (2002) used similar methodology to define aquatic bioregions for Victoria (see also Newall & Wells 2000). More specifically, this study aimed to (i) delineate aquatic bioregions for the South Coast region by grouping catchments using macro-invertebrate data, and (ii) examine the relevance of the existing IBRA regionalisation for in-stream biodiversity in the South Coast region at the catchment scale.

Methods

Study sites

Of a total of 183 sites from 33 waterways (Figure 1), sampled as part of an investigation of the ecological values of rivers in the region during 2006–2008, 146 sites were found to have relatively intact riparian zones, with minimal disturbance, and were thus deemed suitable for use in the present study (Table 1). These rivers represented a variety of systems from across the whole South Coast Region. As the western boundary of the South Coast Region has been under discussion, the Gardner, Shannon and Deep Rivers, all presently designated as South West Region systems, were also included the study. The location of each sampling site was recorded using a hand-held Magellan Meridian GPS using datum GDA 1984.

Table 1

River systems and sites used for determining aquatic bioregions in the South Coast Region. Rivers are listed from west to east.

River system	No. sites sampled
Gardner River	5
Shannon River	5
Deep River	5
Walpole River	2
Frankland Gordon	11
Bow River	2
Kent River	5
Kordabup River	1
Denmark River	4
Hay River	12
Sleeman River	2
Marbellup Brook	15
Seven Mile Creek	1
Bluff Creek	1
Goodga River	2
Limeburners Creek	1
Kalgan River	3
Waychinicup River	3
Pallinup River	7
Bremer River	6
Gairdner River	5
Fitzgerald River	9
Phillips West River	8
Steer River	1
Jerdacuttup River	4
Oldfield River	7
Young River	5
Coobidge Creek	2
Dalyup River	4
Bandy River	2
Coromup River	2
Dailey River	3
Thomas River	1

Macroinvertebrate sampling

For the sampling of macroinvertebrates, a 10 m stretch of stream located at the centre of a study reach was selected. This did not have to be contiguous, but was chosen to include all the in-stream habitats within the study reach. After disturbing the benthos using a combination of kick sampling and loosening of stones and large woody debris (if present) by hand, a 250–µm mesh net was used to sweep over 10 m^2 of streambed. After rinsing off the leaves, twigs and other debris, these were discarded. Each sample was sieved through three grades of sieves (2000 µm, 500 µm and 250 µm) and the contents placed in white trays to facilitate live picking. Using tweezers and plastic pipettes, as many as possible of the macroinvertebrates observed were picked out by two observers in a 30 minute period, placed into labelled containers with 70% ethanol, and returned to the laboratory for further processing, when all macroinvertebrate specimens were identified to the lowest level possible and counted. Consistency of identification with previous studies was achieved by examination of a voucher collection based within the Department of Environment and Conservation (DEC). Species codes for undescribed species were used as per this voucher collection. Debris from the three sieves was also placed in labelled sampling containers with 70% ethanol, and returned to the laboratory for further processing. In particular, macroinvertebrates that had been missed in the live pick were removed, identified and counted.

Measurement of water quality

Selected water quality variables were measured at all sites sampled for fauna. Electrical conductivity (mS/cm), salinity (ppt), pH, temperature (°C), dissolved oxygen content (mg/l and % saturation), oxidation reduction potential (mV) and turbidity (NTU) was measured, in-

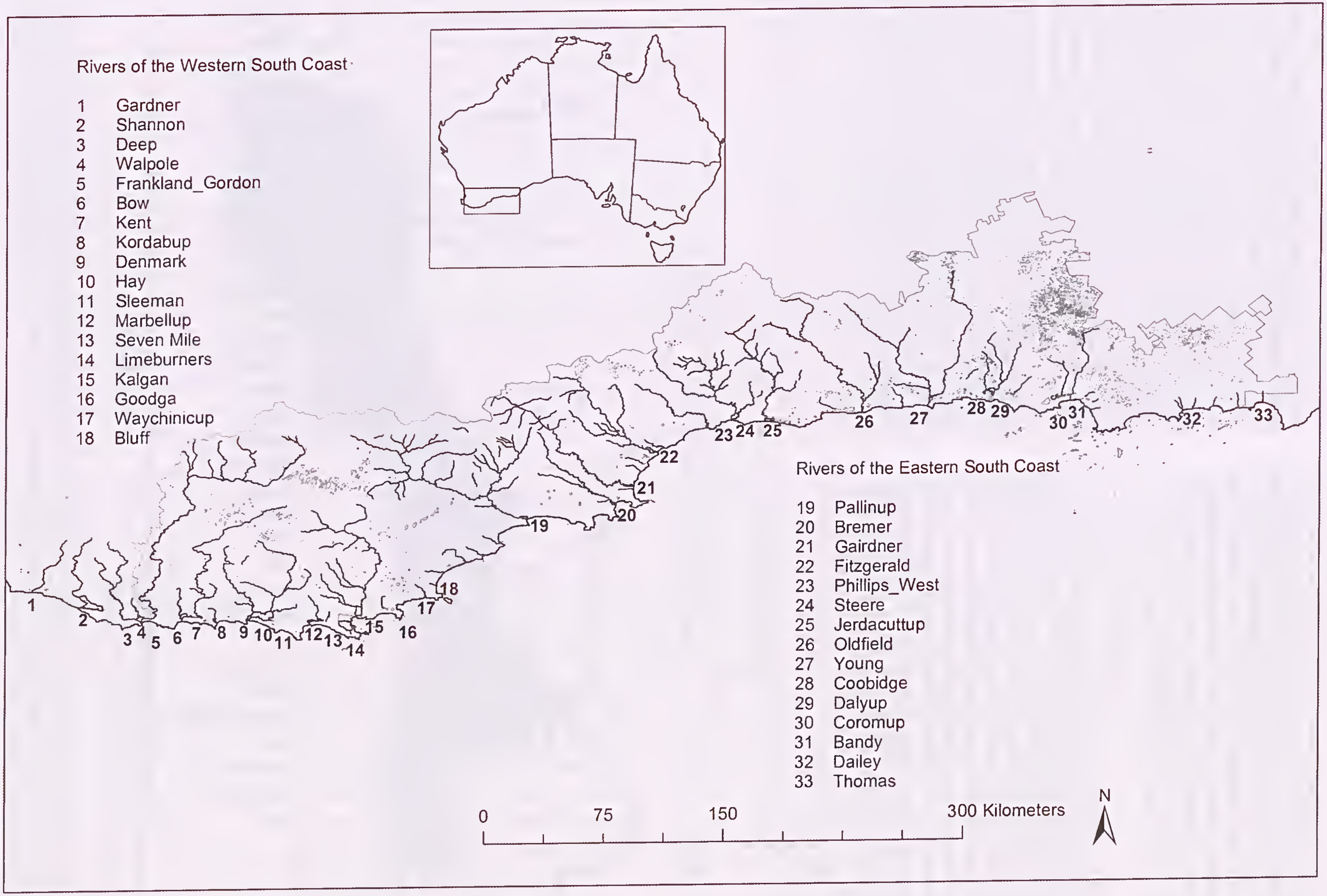

Figure 1. Map of South Coast Region showing location of waterways sampled.

situ, using a Yeo-Kal 611 multi-parameter water analyser. For analysis of total nitrogen and total phosphorus, unfiltered water samples were placed in appropriate containers, kept in a cool, dark place while in the field, and frozen immediately (– 20 °C) upon return to the laboratory. Nutrient analyses were conducted using a Lachat Automated Flow Injection Analyser operated by the Marine and Freshwater Research Laboratory (MAFRL) at Murdoch University, Western Australia.

Data analysis

Multivariate analyses were conducted to characterise the waterways based on invertebrate composition using the software package PRIMER v 6 (Primer-E Ltd). This software package consists of a range of univariate, graphical and multivariate routines for analysing matrices of species by samples (Clarke & Warwick 1994). Macroinvertebrate and environmental data were obtained from the 'least impacted' sites sampled for each waterway. These 'least impacted' sites were selected based on scores calculated for the 'width of riparian vegetation' and the occurrence and extent of degradation processes such as erosion, sedimentation, and weed infestation. Width of riparian zone was scored as follows: 0 = riparian vegetation absent, 1 = < 5m in width, 2 = 5–20m, 3 = 20–100m and 4 = > 100m. The presence of erosion, sedimentation and weed infestation in a given area was scored as follows: 0 = covering 0–5% of area assessed, 1 = 5–20%, 2 = 20–50% and 3 = >50%. Scores for the three degradation processes were added together to obtain an overall score for environmental degradation. Sites which had relatively intact riparian vegetation (scores of 3 or 4 for riparian width), and low levels of environmental degradation (overall score of 5 or less) were considered as being least impacted by threatening processes, and thus were used for the analyses. Data from all sites for each river system (catchment) were combined, and macro-invertebrate data was converted to presence/absence data before analysis (see Higgins *et al.* 2005). Following the calculation of Bray-Curtis dissimilarity measures, a cluster analysis was conducted using unweighted pair groups with mean averaging (UPGMA), and the result plotted as a dendrogram. Characteristic macroinvertebrate species (referred to as 'indicator' species) were determined for each of the

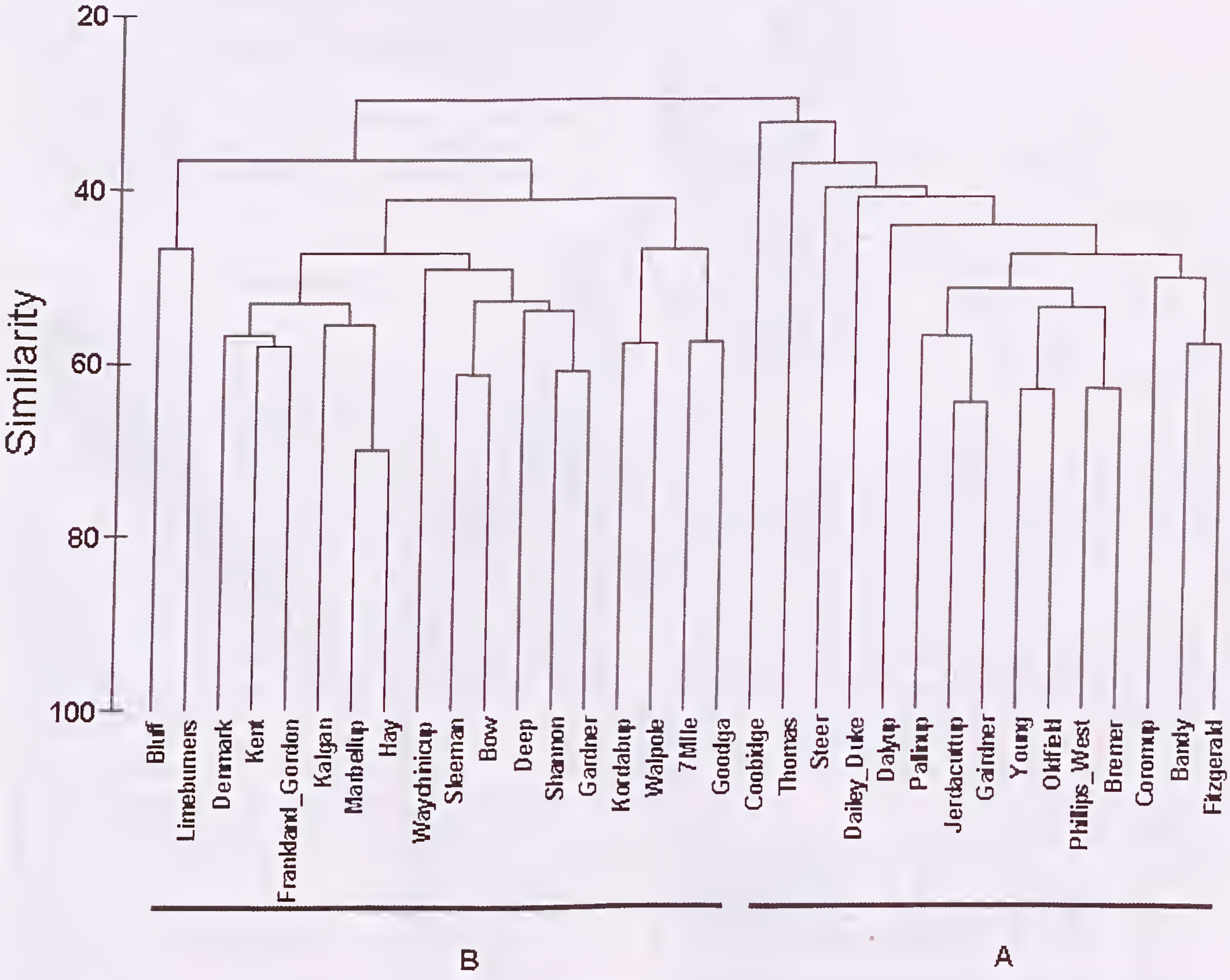

Figure 2. Dendrogram resulting from a hierarchical classification of rivers of the South Coast Region using macroinvertebrate data, showing the existence of two broad aquatic bioregions, (A) Eastern South Coast and (B) Western South Coast. Symbols indicate IBRA bioregions or subregions as follows: closed triangles, Recherche subregion; open triangles, Fitzgerald subregion; closed squares, Jarrah Forest bioregion; open squares, Warren bioregion.

bioregions using the SIMPER subroutine in PRIMER. In order to test the null hypothesis that there were no assemblage differences between the IBRA subregions, an analysis of similarities (ANOSIM) was conducted. Pairwise R values resulting from these analyses give an absolute measure of how well separated the groups are, ranging from a value of 0 for groups which are indistinguishable, to a value of 1, where all similarities within groups are less than any similarity between groups. For cases of few replicates, these pairwise R values can be interpreted as follows: R > 0.75, groups well separated; R > 0.50, groups overlapping but clearly different, and R < 0.25, groups poorly differentiated (Clarke & Warwick 1994).

After delineating bioregions using macroinvertebrate data, water quality data measured at the time of biological sampling (pH, salinity, turbidity, total nitrogen, total phosphorus and dissolved oxygen) were used to provide general descriptions of each bioregion. The mean total number of species (referred to as 'species richness' in the text) collected in a river system, as well as the mean numbers of mayfly, stonefly and caddisfly species (orders Ephemeroptera, Plecoptera and Trichoptera, the so-called 'EPT' taxa), macrocrustaceans (orders Decapoda, Amphipoda and Isopoda), microcrustaceans (classes Copepoda, Ostracoda and Branchiopoda), mites (order Acarina), beetles (order Coeloptera), true flies (order Diptera), bugs (order Hemiptera), dragonflies and damselflies (order Odonata) and snails, limpets and mussels (phylum Mollusca) were also determined for each bioregion. In order to test for significant differences between the two bioregions for water quality and biological variables, t-tests were conducted using the software statistical package GenStat.

Results

Delineation of bioregions

Based on a hierarchical classification using macroinvertebrate data, two distinct aquatic bioregions were recognized for the South Coast region: (i) Western South Coast, consisting of river systems lying from Gardner River in the west to Bluff River, and (ii) Eastern South Coast, consisting of the Pallinup River through to the Thomas River in the east (Figure 2). The two aquatic bioregions coincided with the geographical location of the river systems analysed (Figure 3).

Alignment of the two proposed aquatic bioregions with the IBRA bioregions was variable. The Eastern South Coast aquatic bioregion proposed in this study largely coincided with the Esperance Plains IBRA bioregion, with 15 of 17 rivers located in the IBRA Esperance Plains (ESP) bioregion clustering together. However, the grouping of rivers within the Eastern South Coast aquatic bioregion did not align with the two IBRA

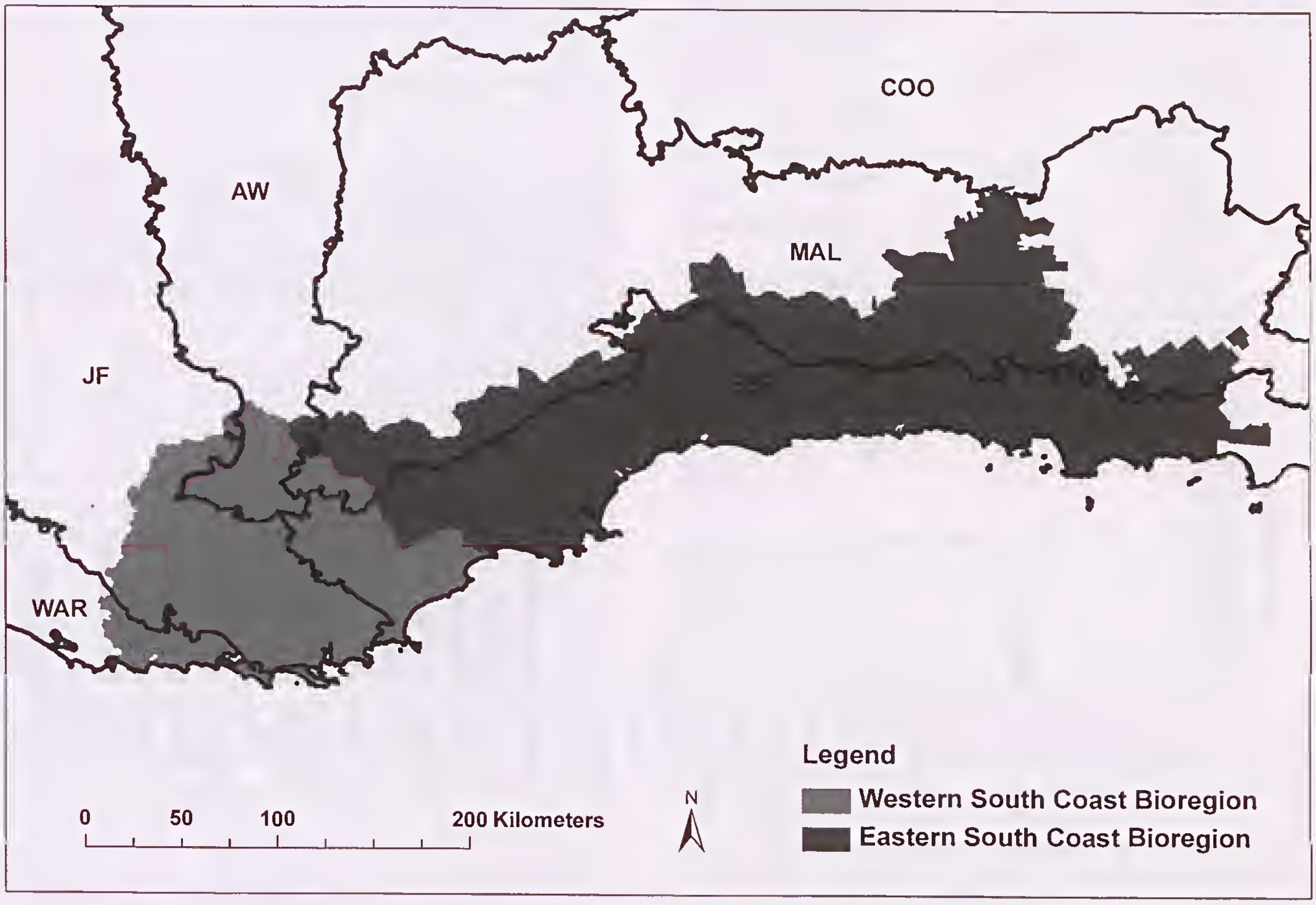

Figure 3. Map of South Coast Region showing location of aquatic bioregions, and boundaries of IBRA bioregions. ESP = Esperance Plains; WAR = Warren; JF = Jarrah Forest.

sub-regions that make up the Esperance Plains bioregion (Table 2). Rivers located in the Recherche sub-region (ESP2) were not more similar to each other than to systems located in the Fitzgerald sub-region (ESP1), and thus these two sub-regions were poorly differentiated (ANOSIM, R = 0.001, p = 0.4). In addition, the Bluff and Waychinicup Rivers (which fall into the Esperance Plains IBRA bioregion) grouped together with rivers located in the Warren and Jarrah Forest IBRA bioregions. All of the 16 rivers that fell into either the IBRA Warren or Jarrah Forest bioregions formed a single cluster which did not subdivide according to IBRA bioregions (R = 0.155, p = 0.06 for pairwise comparison of Jarrah Forest and Warren bioregions).

Water quality

Table 3 summarizes selected water quality parameters associated with each of the two aquatic bioregions defined using macroinvertebrate data. Rivers belonging to the Eastern South Coast aquatic bioregion were significantly more saline, slightly more alkaline, and had higher levels of total nitrogen than those belonging to the Western South Coast aquatic bioregion (t-test, p < 0.05). Rivers of both aquatic bioregions had similar levels of turbidity, dissolved oxygen and total phosphorus levels (t-test, p > 0.05). The bioregionalisation resulting from the use of invertebrate data was associated with a strong salinity gradient (Figure 4), with river systems falling into the Eastern South Coast region being naturally more saline than those falling into the Western South Coast aquatic bioregion.

Table 2

Results of pairwise comparisons using ANOSIM, showing R-values and significance levels. ESP1 = Fitzgerald sub-region; ESP2 = Recherche sub-region; JF2 = Southern Jarrah Forest sub-region; WAR = Warren bioregion.

Pairwise comparison	R-value	Significance level
ESP2, ESP1	0.001	40%
ESP2, JF2	0.830	0.1%
ESP2, WAR	0.854	0.1%
ESP1, JF2	0.327	1.0%
ESP1, WAR	0.441	0.6%
JF2, WAR	0.155	5.7%

Table 3

Water quality parameters associated with each of the two aquatic bioregions defined using macroinvertebrate data.

Parameter	Eastern South Coast bioregion	Western South Coast bioregion
Salinity (ppt)		
Minimum-maximum	6.45–43.84	0.17–10.52
Mean	23.29	1.50
Standard deviation	10.67	2.60
pH		
Minimum-maximum	4.39–8.74	4.35–8.04
Mean	7.38	6.07
Standard deviation	1.07	0.87
Turbidity (NTU)		
Minimum-maximum	0.0–167.6	0.65–32.17
Mean	24.7	13.83
Standard deviation	41.2	9.77
Total nitrogen (µg/l)		
Minimum-maximum	460–2833	195–1800
Mean	1483	935
Standard deviation	753	457
Total phosphorus (µg/l		
Minimum-maximum	7.0–140.9	9–430
Mean	54.3	85
Standard deviation	42.5	118
Dissolved oxygen (mg/l)		
Minimum-maximum	7.01–13.1	6.44–10.4
Mean	9.26	8.97
Standard deviation	1.97	1.13

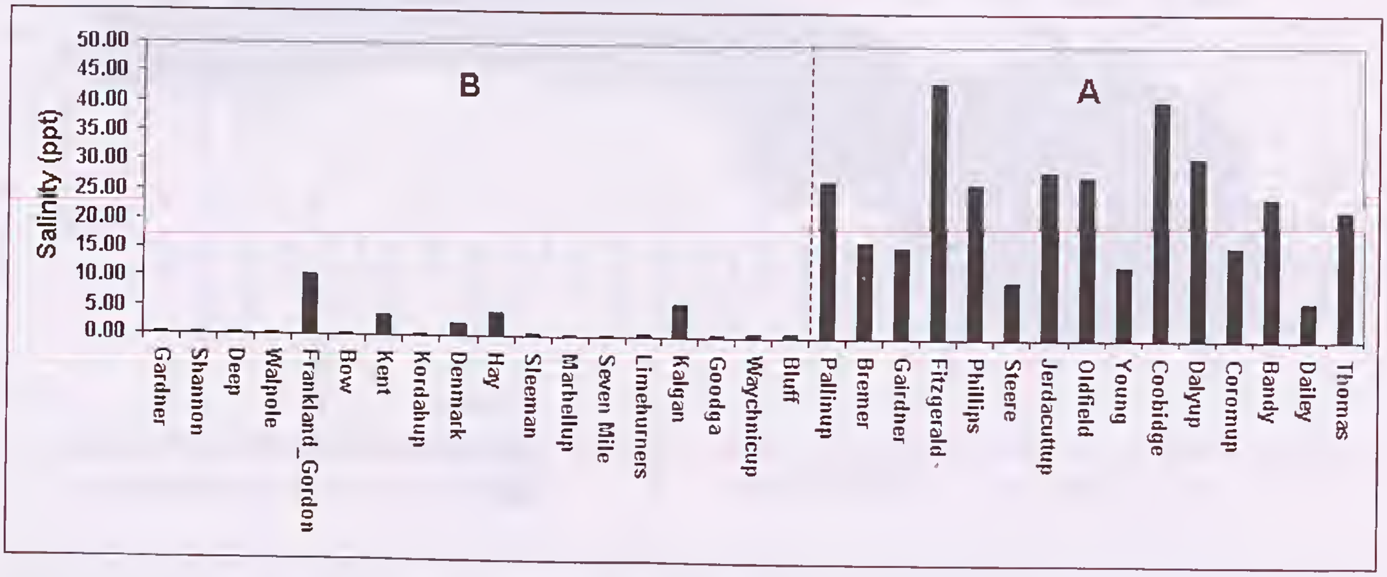

Figure 4. Plot of average salinity recorded for minimally impacted sites sampled from 33 river systems in the South Coast Region. Rivers have been plotted in geographical order from west to east.

In-stream biodiversity

Total species richness ranged from 15 to 79 taxa for river systems in the Eastern South Coast bioregion, and values ranged from 29 to 134 taxa for rivers in the Western South Coast bioregion (Table 4). Average total species richness (69.7) was significantly higher for the Western South Coast aquatic bioregion than for the Eastern South Coast bioregion (45.0) (t-test, $p < 0.05$).

A commonly used biotic index in the assessment of river health is the EPT index. This index is obtained by summing the total number of mayfly (order Ephemeroptera), stonefly (Plecoptera) and caddisfly species (Trichoptera). A significant proportion of the species that make up this index for the South Coast Region are endemic to southwestern Australia. The number of EPT taxa ranged from 0 to 6 for river systems in the Eastern South Coast bioregion, while values ranged from 2 to 25 for rivers in the Western South Coast bioregion (Table 3). Average EPT species richness (12.4) was significantly higher for the Western South Coast aquatic bioregion than for the Eastern South Coast bioregion (2.5) (t-test, $p < 0.05$). Rivers with particularly high numbers of EPT taxa for the Western South Coast bioregion were the Gardner, Shannon and Hay Rivers and Marbellup Brook.

Table 4

Total species richness, and species richness for selected groups for the two aquatic bioregions in the South Coast Region. Means that are significantly different are indicated by different letters, means that are not significantly different share the same letter.

Parameter	Eastern South Coast bioregion	Western South Coast bioregion
Total species richness		
Minimum-maximum	15 – 79	29 – 134
Mean	45^{a}	69.7^{b}
Standard deviation	20.2	31.4
EPT (mayflies, stoneflies, caddisflies)		
Minimum-maximum	0 – 6	2 – 25
Mean	2.47^{a}	12.44^{b}
Standard deviation	1.69	6.45
Macrocrustaceans (decapods, amphipods and isopods)		
Minimum-maximum	1 – 5	1 – 8
Mean	3.00^{a}	4.22^{b}
Standard deviation	1.20	1.96
Microcrustaceans (copepods, ostracods and branchiopods)		
Minimum-maximum	1 – 14	2 – 15
Mean	7.20^{a}	7.22^{a}
Standard deviation	3.78	3.61
Acarina (mites)		
Minimum-maximum	0 – 5	0 – 13
Mean	2.07^{a}	7.61^{b}
Standard deviation	1.49	3.63
Coleoptera (beetles)		
Minimum-maximum	1 – 25	1 – 31
Mean	8.7^{a}	11.7^{a}
Standard deviation	6.63	9.22
Diptera (true flies)		
Minimum-maximum	5 – 13	6 – 22
Mean	8.80^{a}	11.22^{a}
Standard deviation	2.34	4.32
Hemiptera (bugs)		
Minimum-maximum	0 – 7	0 – 6
Mean	2.87^{a}	2.06^{a}
Standard deviation	2.39	2.01
Odonata (dragonflies and damselflies)		
Minimum-maximum	0 – 8	1 – 13
Mean	2.87^{a}	5.28^{b}
Standard deviation	2.53	3.48
Mollusca (snails, limpets and mussels)		
Minimum-maximum	0 – 5	0 – 5
Mean	1.93^{a}	2.11^{a}
Standard deviation	1.39	1.68

Significant taxa

Many taxa were significant in terms of distinguishing the two aquatic bioregions (Table 5). For example, the amphipod *Perthia branchialis* was common in rivers of the Western South Coast bioregion (occurring in 88.9% of rivers sampled), but was absent in rivers in the Eastern South Coast bioregion. An undescribed paramelitid species was absent in rivers of the Western South Coast bioregion, but occurred in seven (46.7%) rivers in the Eastern South Coast bioregion. The distribution of several species of caddisfly (Order Trichoptera) also proved significant in terms of distinguishing the two aquatic bioregions. Forty-three species of caddisflies (order Trichoptera), from nine families have been recorded in southwestern Australia (Sutcliffe 2003), with about 70% of these being endemic to the region. These regionally endemic species generally coincide with the higher rainfall areas of the region, and a certain proportion of these species show further restriction within the high rainfall area (Sutcliffe 2003). A total of 35 species (in seven families) of caddisflies were collected in the present study, all of which occurred in the Western South Coast bioregion, while only six caddisfly species (all in the Family Leptoceridae) occurred in the Eastern South Coast bioregion. The most common of the 22 species in the family Leptoceridae found in the South Coast region were the southwestern Australian endemics, *Condocerus aptus* (72.2% of rivers in the Western South Coast bioregion), and *Lectrides paralis* (77.8%). Three species were found more frequently in the Eastern South Coast region than in rivers of the Western South Coast bioregion. *Symphitoneuria wheeleri*, known from South Australia and southwestern Australia and thought to be closely associated with saline waters (St Clair 2000) was found in 73.3% of rivers sampled in the Eastern South Coast bioregion, and only 11.1% (the Kalgan and Frankland Gordon River systems) of rivers in the Western South Coast bioregion. Similarly, *Notolina spira*, known to occur widely in Australia (St Clair 2000), was found in more Eastern South Coast bioregion rivers (40%) than in Western South Coast bioregion rivers (22.2%). Two species of the family Hydropsychidae were found in the Western South Coast bioregion, one of which is the southwestern Australian endemic, *Smicrophylax australis*. This species occurred in 44.4% of rivers, from the Gardner River through to the Kalgan River, and was absent in Eastern South Coast rivers.

Table 5

Role of individual species in contributing to the separation between the aquatic bioregions, listed in decreasing order of contributions.

Taxa	Eastern South Coast: Average abundance	Western South Coast: Average abundance	% contribution	Cumulative %
Perthia branchialis (Nicholls, 1974)	0	0.89	1.22	1.22
Hygrobatidae spp	0	0.89	1.17	2.39
Oxus spp	0	0.83	1.11	3.5
Lectrides parilis Neboiss, 1982	0	0.78	1.05	4.56
Stratiomyidae sp	0.93	0.28	1.03	5.59
Simuliidae spp.	0.13	0.83	1.02	6.6
Necterosoma penicillatus Clark, 1862	0.87	0.28	0.98	7.58
Tipulidae spp.	0.13	0.83	0.97	8.55
Tasmanocoenus tillyardi (Lestage, 1938)	0	0.72	0.96	9.52
Condocerus aptus Neboiss, 1982	0	0.72	0.94	10.46
Symphitoneuria wheeleri Banks, 1939	0.73	0.11	0.93	11.39
Newmanoperla exigua (Kimmins, 1951)	0	0.67	0.93	12.31
Coxiella spp.	0.73	0.11	0.91	13.22
Austroaeshna anacantha (Tillyard)	0	0.67	0.9	14.12
Unionicolidae spp	0.13	0.72	0.83	14.95
Cladocera spp.	0.4	0.89	0.83	15.78
Nematoda sp.	0.33	0.78	0.82	16.6
Empididae sp.	0.13	0.67	0.82	17.42
Scirtidae sp.	0.13	0.67	0.81	18.24
Ostracoda sp.1	0.13	0.67	0.8	19.04
Bibulmena kadjina Dean, 1987	0	0.56	0.8	19.83
Laccobius zietzi (Blackburn, 1895)	0.6	0	0.76	20.6
Calanoida spp	0.87	0.5	0.76	21.36
Hemicordulia tau (Selys, 1871)	0.13	0.61	0.76	22.11
Cherax pressii (Erichson, 1846)	0.13	0.61	0.75	22.86
Sternopriscus marginatus Watts, 1978	0	0.61	0.75	23.61
Miniargiolestes minimus (Tillyard, 1908)	0	0.56	0.73	24.34
Austrolestes annulosus (Selys)	0.6	0.17	0.73	25.07
Nyungara bunni Dean, 1987	0	0.56	0.72	25.79
Austragrion cyane (Selys, 1876)	0.6	0.28	0.71	26.5
Ferrissia sp	0	0.5	0.7	27.19
Ephidridae sp2	0.53	0.06	0.69	27.89
Trombidioidea spp	0.53	0.61	0.69	28.58
Ocetis sp.	0.47	0.61	0.69	29.26
Gomphodella spp	0	0.5	0.69	29.95
Palaemonetes australis Dakin, 1915	0.47	0.56	0.68	30.63
Isotomidae sp.	0.33	0.56	0.68	31.31
Veliidae/Hebridae spp.	0.6	0.67	0.67	31.98
Westralunio spp.	0.53	0.17	0.67	32.65
Orbatididae spp	0.6	0.78	0.65	33.3
Mytilocypris tasmanica chapmani McKenzie	0.53	0.17	0.65	33.95
Limbodessus inornatus (Sharp, 1882)	0.13	0.56	0.64	34.59
Limnoxenus zelandicus (Broun)	0.4	0.44	0.64	35.23
Paramelitidae sp.	0.47	0	0.62	35.85
Austrogomphus lateralis (Selys, 1873)	0.13	0.44	0.62	36.48
Micronecta robusta Hale, 1922	0.47	0.33	0.62	37.1
Ilyocypris australiensis Sars, 1889	0.47	0.22	0.61	37.7
Mesostigmata spp	0.13	0.44	0.6	38.31
Mytilocypris ambiguosa De Deckker, 1978	0.47	0.11	0.6	38.9
Harpacticoida spp	0.8	0.72	0.58	39.48
Hypogastruridae sp.	0.87	0.67	0.58	40.06
Orthocladinae spp	0.6	1	0.57	40.63
Paracymus pygmaeus (MacLeay, 1871)	0.13	0.5	0.57	41.2
Lepidoptera spp.	0.27	0.44	0.56	41.76
Sphaeromatidae sp	0.4	0	0.56	42.32
Culicidae Aedes spp.	0.4	0.11	0.56	42.88
Smicrophylax australis (Ulmer, 1908)	0	0.44	0.56	43.43
Ephidridae sp1	0.4	0	0.55	43.98
Sminthuridae sp.	0.27	0.33	0.55	44.53
Notalina spira St Clair, 1991	0.4	0.22	0.54	45.07
Aeshna brevistyla (Rambur)	0.27	0.33	0.54	45.61
Tanyderidae sp	0	0.39	0.54	46.16
Necterosoma regulare Sharp, 1882	0.4	0.11	0.54	46.7
Tabanidae sp	0.33	0.22	0.54	47.23
Chrysomelidae spp	0.13	0.39	0.53	47.76
Notodromadidae spp.	0.33	0.33	0.53	48.29
Triplectides australicus Banks, 1939	0.13	0.44	0.53	48.81
Arrenurus sp	0.2	0.33	0.52	49.34
Sternopriscus multimaculatus (Clark, 1862)	0.27	0.33	0.52	49.86
Curculionidae spp.	0.13	0.39	0.52	50.37
Notoperata tenax Neboiss, 1982	0	0.39	0.51	50.88

Mayflies (Order Ephemeroptera) and stoneflies (Order Plecoptera) were collected from a number of Western South Coast rivers, but were absent in rivers of the Eastern South Coast bioregion. Nine mayfly species were collected from the South Coast, seven of which belonged to the family Leptophlebiidae, the most diverse of the Australian mayfly families. Of these, six are known to be endemic to southwestern Australia. The endemic species *Bibulmena kadjina* was collected from more than half of the rivers sampled in the Western South Coast bioregion (55.6%). *Tasmanocoenus tillyardi* was also relatively common, occurring in 72% of rivers sampled. Despite high diversity in eastern Australia, only four species of stoneflies are known from Western Australia (Hynes & Bunn 1984). All of these are regionally endemic. The stonefly species *Newmanoperla exigua* occurred in 66.7% of the rivers of the Western South Coast bioregion and *Leptoperla australica* was found in 38.9% of rivers in this bioregion. Both species were absent in rivers of the Eastern South Coast bioregion.

Discussion

Classification of rivers based on macroinvertebrate data revealed two distinct aquatic bioregions in the South Coast region – the Western South Coast aquatic bioregion stretching from the Gardner River in the west to the Bluff River in the east, and the Eastern South Coast aquatic bioregion stretching from the Pallinup River in the west to the Thomas River in the east. These two site groups support the notion of large, relatively homogeneous regional patterns for aquatic biodiversity distribution in the South Coast Region of southwestern Australia. This is despite the fact that classifications based on numeric agglomerative approaches can often be characterised by groups with complex spatial patterns, where a group can have more than one geographical occurrence (Mackey *et al.* 2008). In order to determine whether these aquatic bioregions relate to the 'aquatic zoogeographic units' or the 'ecological drainage units' suggested by Higgins *et al.* (2005), a bioregionalisation for the whole of Western Australia would need to be conducted. Higgins *et al.* (2005) have suggested a hierarchical classification framework of four spatial levels for freshwater classification and biodiversity conservation planning – an aquatic zoogeographic unit; ecological drainage units within one aquatic zoogeographic unit; aquatic ecological systems within one ecological drainage unit; and macrohabitats within one aquatic ecological system. Aquatic zoogeographic units (generally 10,000–100,000 km^2) are distinguished by regional patterns of zoogeography, while ecological drainage units delineate areas with similar biotic patterns, but on a finer scale (1,000–10,000 km^2). The recognition of the latter through multivariate analysis of common species presence/absence data, as was adopted in this study, is a recommended approach (Higgins *et al.* 2005).

The recognition of aquatic bioregions is important for a number of reasons. For example, the relatively low Observed/Expected (O/E) scores (thus implying poor condition) obtained by Halse *et al.* (2007) for naturally saline, 'reference' (minimally disturbed) sites on the South Coast highlights the importance of assessing the condition (and ecological value) of rivers relative to their type. The AusRivAS (Australian River Assessment System) models used by these authors contained mainly freshwater reference site groups. These are clearly inappropriate for assessing naturally saline systems belonging to the Eastern South Coast aquatic bioregion, suggesting that the AusRivAS models for Western Australia should be refined to account for bioregional differences. Halse *et al.* (2002) have suggested that a regionally-based AusRivAS model needs to be developed to assess rivers located in the eastern part of the South Coast region, and that this model should use salinity as a predictor variable to assign sites to reference groups. These authors attributed the poor O/E scores for reference sites in their results for this region to the occurrence of high salinities in the area. The development of 'bioregion-specific' AusRivAS models for the whole of Western Australia could improve the sensitivity of this approach, enabling the detection of low to moderate levels of disturbance. Use of biotic indices such as the SIGNAL (Stream Invertebrate grade Number Average Level) index (Chessman 1995) and the Ephemeroptera-Plecoptera-Trichoptera (EPT) index would also be further enhanced if natural regional differences were to be incorporated into their use.

The results of this study suggest that the IBRA bioregions and sub-regions need to be further tested for applicability for describing aquatic biodiversity. As the present study was aimed at producing a broad, regional-scale classification, resulting in the recognition of homogeneous geographical regions, it was conducted at the catchment scale, rather than at the sub-catchment scale. While the Eastern South Coast aquatic bioregion proposed in this study aligns well with the Esperance Plains bioregion defined by IBRA, the catchment level analysis conducted in this study was not of a fine enough resolution to test the validity of using the Warren and Jarrah Forest IBRA bioregions for explaining in-stream biodiversity patterns. Although there are 13 rivers located in the Warren bioregion, only six of these (Gardner, Shannon, Deep, Walpole, Scott and Inlet Rivers) have their main catchments within the bioregion. Although assigned to this bioregion in the catchment-level analysis, the Kent, Frankland Gordon and Bow Rivers have only their lower reaches in the bioregion. The catchment scale approach, however, could be successfully used to test the applicability of the two IBRA sub-regions defined for the Esperance Plains bioregion, as the catchments of rivers in this bioregion fell largely in either one or other of these two sub-regions. This analysis showed that the existence of the two terrestrially derived IBRA sub-regions (Fitzgerald and Recherche) was not supported by the aquatic fauna.

Many species proved significant in distinguishing the two bioregions, including two species of amphipods, the perthiid *P. branchialis* and an undescribed paramelitid species. The families Perthiidae and Paramelitidae are members of the Superfamily Crangonyctoidea, the most widespread and significant of Australian freshwater groups (Bradbury & Williams 1999). There is only one known genus in the family Perthiidae, with two species (*Perthia branchialis* and *P. acutitelson*), both of which are confined to southwestern Western Australia. To date, 10 paramelitid species (five species in the genus *Uroctena*, one species each in the genera *Hurleya*, *Protocrangonyx*, *Toulrabia, Totgammarus* and *Pilbarus*) have been described from Western Australia (Bradbury & Williams 1999). The species collected from the rivers of the Eastern South Coast bioregion was not one of these species. This amphipod was generally collected from sites along the lower reaches of rivers, and has a distribution ranging from the Jerdacuttup River through to the Thomas River, in the eastern part of the Eastern South Coast bioregion. This species requires taxonomic description.

Conclusions

The successful implementation of a biotic classification to delineate aquatic bioregions for the South Coast Region indicates that the method may be easily instituted and adapted for other regions within Western Australia. It certainly would be beneficial to extend the hierarchical classification approach adopted in the present study to the whole of the State of Western Australia. Such an approach would recognise larger biogeographical regions, subdivided into subregions, which are further characterised by variation among sites within subregions. Such a classification would be an essential first step in a larger process of conservation planning for freshwater biodiversity in Western Australia. The aquatic bioregionalisation would facilitate the assessment of river health and conservation through the setting of meaningful regional water quality guidelines, it would allow the selection of 'representative' river systems and monitoring sites within the context of a larger classification system of river types, and would also facilitate the development of broadly applicable management strategies and frameworks by water resource managers.

Although using biotic attributes to classify and define groups of waterways is likely to lead to the recognition of ecological meaningful classifications, this approach is data intensive, and can be hampered by the time and resources needed to collect biotic data. Past sampling program, such as the Australian-wide 'Australian River Assessment System' (AusRivAS) program have generated large macroinvertebrate datasets, and these have been used by some authors to define interim aquatic bioregions in other parts of Australia (*e.g.*, Turak *et al.* 1999). Once specimens have been identified to species level to improve resolution, these datasets could be used to define, and refine aquatic bioregions for other parts of Western Australia. The AusRivAS program in Western Australia sampled 477 sites in 1997–2000 and a further 188 sites in 2004 (Halse *et al.* 2007), thus generating a potentially useful database for delineating bioregions across Western Australia. Newall & Wells (2000) undertook a similar approach when they sourced large data sets for Victoria that had been gathered for State and national water quality monitoring programs (e.g., the Victorian component of the Monitoring River Health Initiative), and defined bioregions for the State.

Additional sampling would better define the boundary between two aquatic bioregions proposed for the South Coast region. A 'grey' area still exists in the area lying between the Bluff and Pallinup Rivers, as systems lying in this area (Wongerup Creek, Mulloculiop Creek, Cordinup River, Willyun Creek and Eyre River) were not included in this study. Inclusion of these systems in future analyses will further refine the exact location of bioregion boundaries, and will also confirm whether a transitional zone exists between the two broad aquatic bioregions. More data analyses at the subcatchment scale would also be required to test whether the two broad aquatic bioregions can be divided into aquatic sub-regions. It is probable that at the finer subregional scale, groupings will reflect the longitudinal nature of rivers, with upper reaches of adjacent systems being more similar to each other than the upper and lower reaches of a single system.

In addition, it is possible that the bioregionalisation produced here based on macro-invertebrates may not reflect differences in other aquatic biotic groups such as fish or plants, leading to the recommendation that the potential commonality in regionalisations of different groups of aquatic biota needs to be established (Growns & West 2008). Future research projects can thus treat the bioregionalisation proposed here as a working hypothesis (see Mackey *et al.* 2008) that can be tested for applicability to other aquatic groups as well as other types of waterbodies such as wetlands and lakes.

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